AD____________________

Award Number: W81XWH-04-C-0002

TITLE: Diagnostic Methods for Predicting Performance Impairment Associated with Combat Stress

PRINCIPAL INVESTIGATOR: Gerald Matthews, Ph.D.
Joel S. Warm, Ph.D.
David Washburn, Ph.D.

CONTRACTING ORGANIZATION: University of Cincinnati
Cincinnati OH 45208

REPORT DATE: August 2007

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
01-08-2007

**2. REPORT TYPE**
Final

**3. DATES COVERED** *(From - To)*
1 DEC 2003 - 31 JUL 2007

**4. TITLE AND SUBTITLE**
Diagnostic Methods for Predicting Performance Impairment Associated with Combat Stress

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**
W81XWH-04-C-0002

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Gerald Matthews, Ph.D., Joel S. Warm, Ph.D., David Washburn, Ph.D.

E-Mail: Joel.Warm@uc.edu

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
University of Cincinnati
Cincinnati OH 45208

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**
Approved for Public Release; Distribution Unlimited

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
This report reviews the third year of research on the diagnostic utility of psychophysiological indicthat may predict the current and future functional efficiency of the soldier. The research focuses especially on the measurement of cerebral bloodflow velocity (CBFV) using transcranial Doppler sonography (TCD), together with additional indices including salivary cortisol and subjective state. Two studies at the University of Cincinnati demonstrated that CBFVdeclines during cognitive vigilancand during simulated driving, extending prior results from sensory vigilance tasks. In addition, phasBloodflow responses to a short task battery predicted cognitive vigilance. Predictive validity was increased by including subjective state measures in a multivariate model. Research at Georgia State University, employing simulated military tasks representing sentry duty, peacekeeping operations,andtactical decision making. These studies confirmed that CBFV correlates with various performance indices, indicating that the technique may have diagnostic utility not just for vigilance, but also fmilitary decision-making. Attentional skills and eye movement indices were also found to have diagnostic utility. The report concludes with a summary of the main findings from the three years of research, and recommendations for future studies to translate the research into applied techniques fodiagnostic monitoring and prediction in military environments.

**15. SUBJECT TERMS**
Stress, cerebral bloodflow, performance, vigilance, sustained attention, fatigue, vehicle driving, individual differences, workload

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| | | | | | USAMRMC |
| U | U | U | UU | 63 | 19b. TELEPHONE NUMBER *(include area code)* |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std. Z39.18

## Table of Contents

## INTRODUCTION

Sustained military operations, including combat, often elicit psychophysiological states of stress and fatigue that may compromise the soldier's ability to maintain vigilance and situation awareness. This report describes the accomplishments of the *final year* of a three-year program of research on the diagnostic utility of psychophysiological indices that may predict current and future functional efficiency. The research focuses especially on the measurement of cerebral bloodflow velocity (CBFV) using transcranial Doppler sonography (TCD), as well as additional indices of salivary cortisol, subjective stress state, and eye movement measurements. The principal research aims are to evaluate the utility of TCD in monitoring fitness to perform concurrently with performance, and to explore strategies for using TCD as a predictor of future performance. Experiments on vigilance and other tasks requiring sustained attention were conducted at the University of Cincinnati (UC) and Georgia State University (GSU) in pursuit of these objectives.

The first study performed at UC tested whether CBFV and subjective responses to a short task battery predicted subsequent performance on a cognitive vigilance task requiring working memory. The principal findings from a previous study of sensory vigilance were replicated; both CBFV and subjective task engagement were diagnostic of future performance. A multiple regression analysis suggested that around 20% of the variance at the end of the vigil could be predicted; a level of predictive validity that exceeds typical findings from previous vigilance research. Manipulation checks confirmed that the vigilance task elicited subjective fatigue, performance decrement and declining CBFV in both hemispheres, as expected. Furthermore, measurement of phasic increases in CBFV to the initial task battery was shown to be statistically reliable and psychologically meaningful. The second UC study investigated CBFV during performance of a simulated driving task. The task was configured to be fatiguing, and inclusive of a vigilance decrement. Results showed CBFV decline in both hemispheres during driving, establishing for the first time that TCD may be applied to monitoring execution of a skill integrating multiple task components. However, in this study, individual differences in TCD were not predictive of performance.

Studies at GSU explored the relationships between TCD and performance on a range of simulations of military tasks. These included a Watchkeeper task that simulates sentry duty, requiring the participant to detect and shoot threat images. A Peacekeeper task required a 'shoot/don't shoot' decision in discriminating targets and non-targets presented in a street environment. A defensive systems operation task simulates tactical decision-making in choosing between alternative responses to threats of differing severity. Findings from these studies established several associations between CBFV and performance. CBFV was found to decline during performance of the Watchkeeper task; changes in CBFV were modestly but reliably related to performance. On both Watchkeeper and Peacekeeper tasks, performance was related to lateralization of bloodflow; fast and accurate decision related to relatively higher bloodflow in the left hemisphere. Data from the defensive systems operation task suggested that CBFV may also indicate over-reaction to threat. A final study linked CBFV to prediction of uncertainty in decision making over subjective uncertainty measures. These results establish the relevance of CBFV to simulations of military tasks, and indicate that it may diagnostic of some aspects of decision-making as well as vigilance. The GSU studies also suggested the measures of eye movements and attentional skills may complement TCD in the prediction and monitoring of sustained performance.

## BODY OF REPORT

Work Completed at the University of Cincinnati

### UC- STUDY 1: DIAGNOSTIC PREDICTORS OF COGNITIVE VIGILANCE

Our previous study, reported by Matthews, Warm and Washburn (2004, 2005), investigated a range of predictors of sensory vigilance including bilateral cerebral bloodflow velocity (CBFV) and subjective state (see also Reinerman et al., 2006). A 'two-phase' design was employed in which CBFV response to a short battery of high workload tasks was evaluated as a predictor of a subsequent, longer-duration vigilance task resembling air traffic control. Short, high workload tasks typically induce phasic increases in CBFV that are lateralized according to the processing demands of the task (Stroobant & Vingerhoets, 2000; Tripp & Warm, 2007). These responses may index mobilization of attentional resources and task-directed effort evoked by the performance challenge. Hence, higher phasic CBFV may predict superior vigilance on a subsequent task. The principal findings of this study were as follows:

- The short task battery elicited increases in CBFV that were appropriately lateralized.
- Reliable individual differences in CBFV response to the short battery were demonstrated. Left- and right-hemisphere responses were distinct from one another, but also positively intercorrelated.
- The sensory vigilance task showed temporal decrements in both performance (detection rate) and CBFV, as in previous studies.
- The amplitude of the CBFV response to the short battery predicted superior subsequent vigilance, consistent with a processing resource model. Individual differences in concurrent CBFV were not related to vigilance.
- Subjective state measures demonstrated task-induced stress and fatigue responses; the vigilance task elicited both distress and loss of task engagement.
- Levels of task engagement during the short battery correlated positively with subsequent vigilance performance. Concurrent measures of subjective state and coping also correlated positively with vigilance.
- Salivary cortisol failed to correlate with vigilance.
- It was concluded that concurrent use of both CBFV and subjective measures may provide the most effective technique for evaluating whether soldiers are fit for missions requiring sustained attention.

The aim of this study was to test whether findings generalize to a *cognitive* vigilance task, requiring symbolic processing of stimuli. Military personnel may be required to monitor for critical signals that are defined by symbolic attributes, such as a code identifying the nature of a hostile unit. It may be difficult to maintain vigilance to a series of stimuli of this kind, even if the stimulus elements are readily perceived, so that there is little task load derived from sensory processing. The workload of cognitive vigilance often derives from the working memory load

imposed by the task. Vigilance research has investigated various ‘cognitive’ tasks, such as the Bakan task requiring detection of three successive odd digits in a digit stream, and vigilance decrements are commonly observed (See, Howe, Warm, & Dember 1995).

However, it is unclear whether predictors of sensory vigilance, as established by Matthews et al. (2004, 2005), generalize to cognitive vigilance. The resource model of vigilance (Davies & Parasuraman, 1982; Warm, Matthews & Finomore, in press; Warm & Dember, 1998) attributes loss of vigilance to a general resource that limits performance of both sensory and cognitive tasks. Markers for individual differences in resource availability, including CBFV and subjective task engagement, should thus predict both types of task. Furthermore, performance levels on relatively short, high workload sensory and cognitive vigilance tasks are correlated (Matthews, Davies & Holley, 1993). On the other hand, some resource theorists (e.g., Wickens & Hollands, 1999) advocate a multiple-resource perspective within which separate resource pools may exist for sensory and symbolic processing. In this case, predictors of one resource pool may not generalize to a different resource type, implying that predictors of sensory and cognitive vigilance may differ. There is also some evidence that the sensitivity of vigilance decrement to workload factors may differ somewhat across the two task types (See et al., 1995).

*Aims of the study*

The study aimed to test whether results from the earlier study of sensory vigilance generalized to prediction of a cognitive vigilance task, using a similar design. Hence, the study aimed to compare indices of self-report state, salivary cortisol, and cerebral bloodflow velocity (CBFV) measured by transcranial Doppler sonography (TCD) as predictors of cognitive vigilance performance. The study employed a two-phase design, in which participants performed a short battery of high-workload tasks, followed by a longer vigilance task requiring sustained attention. The general resource model, supported by the previous study (Matthews et al., 2004, 2005), leads to the expectation that both CBFV and subjective task engagement response to the first phase (short battery) should predict performance during the second phase (cognitive vigilance). The study also tested whether personality traits and general cognitive ability related to vigilance

It is also unclear whether TCD can be used to predict loss of performance *in advance of* performance. To the extent that a larger-magnitude CBFV response signals greater availability of resources and/or effort, it can be hypothesized that the phasic increase in bloodflow to short tasks will predict higher levels of CBFV and superior performance on a subsequent, longer vigilance task that is expected to elicit a decline in CBFV.

It is uncertain how CBFV response may align with other subjective and physiological indices that may be linked to the energetics of performance. The study also included measures of salivary cortisol, which may index the activation of a hypothalamic-pituitary-adrenal axis (HPA) corresponding to the well-known ‘fight-or-flight’ response (e.g., Dickerson & Kemeny, 2004). Studies provide conflicting data on how cortisol may relate to performance efficiency, but the measure was included here to test the overlap between CBFV and a widely-used physiological index.

It should be noted that the present research did not seek to take any measures of cardiovascular activity, such as blood pressure or heart rate. It is generally assumed that task-

elicited changes in CBFV do not directly reflect changes in cardiovascular functioning, because of the lateralization of responses across the two cerebral hemispheres according to the information-processing demands of the task (Stroobant & Vingerhoets, 2000; Tripp & Warm, 2008). Our previous reports for USMRMC describe lateralized responses to the short task battery used in the present research. Thus, it is unlikely that the psychogenic component of the CBFV response is linked to cardiovascular activity in any simple way, although further research on the issue would be desirable.

Previous work at UC has established that subjective states may predict performance of vigilance tasks (Matthews & Davies, 1998; Matthews et al., 2001). Our state model discriminates three broad state factors: task engagement (e.g., energy, motivation, alertness), distress (negative affects and low confidence), and worry (self-relevant, intrusive thoughts). Previous studies (e.g., Hitchcock et al., 2003) show that workload parameters of vigilance tasks appear to exert similar effects on both task engagement and CBFV. On this basis, it was hypothesized that task engagement would correlate positively with CBFV. Furthermore, task engagement is a fairly reliable predictor of greater perceptual sensitivity across a range of vigilance tasks and other attentionally demanding tasks (Matthews & Davies, 1998). Thus, it was predicted that task engagement would predict superior vigilance performance. The study also aimed to test whether task engagement and CBFV predict the same variance in performance or whether they function as independent predictors. Recent stress research at UC (e.g., Szalma et al., 2004) has highlighted the role of coping in vigilance, i.e., the person's choice of strategies for dealing with the monotony and stress of the task. To complement the investigation of subjective states, we also included a coping inventory that assesses task-focused, emotion-focused, and avoidance coping. The former strategy was expected to be more effective than the two latter ones in the performance setting.

## Method

The general method for the series of studies is reported by Matthews et al. (2004). Here, we report a summary of the method, together with a more detailed account of the two novel features of the study – the cognitive vigilance task and the addition of a general ability test to the predictor variables. The reader should refer to Matthews et al. (2004) for details of the method not described below.

### *Participants*

There were 107 participants, recruited from UC introductory psychology students, of whom 62% were female. Mean age was 19.9. Inclusion and exclusion criteria are listed in Matthews et al. (2004).

### *Psychophysiological indices*

A Nicolet Companion III TCD unit, with two ultrasound transducers fitted within a head bracket, was used to record bilateral CBFV in the medial cerebral arteries. Previous studies at the

University of Cincinnati (e.g., Hitchcock et al., 2003; Warm & Parasuraman, 2007) have shown that decreases in CBFV are linked to loss of sustained attention.

Salivary cortisol may index the activation of a hypothalamic-pituitary-adrenal axis (HPA), corresponding to the well-known 'fight-or-flight' response (e.g., Dickerson & Kemeny, 2004). Saliva was assayed by having participants chew on a cotton wool 'Salivette', that was sent to an external laboratory for analysis.

*Questionnaire measures*.

The Dundee Stress State Questionnaire (DSSQ: Matthews et al., 1999, 2002) assesses participants' immediate moods, motivations, cognitions and coping strategies, prior to or following task performance. It may be scored for three broad subjective state factors; task engagement, distress and worry. The post-task version also includes a short workload assessment, based on the NASA-TLX (Hart & Staveland, 1988). The Coping Inventory for Stressful Situations (CITS: Matthews & Campbell, 1988) assesses task-focused, emotion-focused and avoidance coping in the specific context of task performance.

*Assessment of general reasoning ability.*

The Letter Series test is an unpublished test of reasoning ability, used in internal research by the Educational Testing Service (ETS: Princeton, NJ). Items require the testee to recognize patterns in letter sequences. It was supplied for use in this study by Dr. Richard D. Roberts, who is a senior research scientist at ETS.

*Cognitive vigilance task.*

A computer was used to present stimuli on a 17" monitor and record all participants' responses. The vigilance task required participants to decode letter sequences. Each item was in two parts. The first part of the item presented a sequence of three coded letters. Each letter was presented singly, at a rate of 1 letter/2 s. The participant must count forward a designated number of places in the alphabet to decode each letter (e.g., A + 1 = B). The second part of the item then presented a further letter sequence; the participant's task was to check whether the three-letter code obtained initially was present in the sequence, in reverse order. Again, letters were presented singly. For example, if the first three letters were decoded as G-T-S, the participant was to respond on detecting the further sequence S-T-G. Participants indicated their detection of a critical signal (matching codes) of this type. In the practice session, participants were familiarized with the stimuli, and practiced with feedback given following errors. In the main task, the participant performed the task for 36 minutes, divided into four continuous 9-min periods of watch, without feedback. CBFV was recorded throughout performance. During each period of watch, a total of 45 items were presented, of which 8 were critical signals. Two measures of performance accuracy were recorded – the proportion of signals correctly detected ('hits'), and the proportion of non-signals to which the participant incorrectly responded ('false alarms').

*Procedure*

The sequence of assessments and tasks was as follows:

| *Time* | *Assessment* |
|---|---|
| 0-5 mins | Saucier Mini-markers for personality |
| 5-10 mins | Letter Series test of reasoning ability |
| 10-20 mins | DSSQ (assessment of subjective state) and saliva sample (stored and later assayed or cortisol) |
| 20-35 mins | A short battery of three demanding tasks, each lasting 2 minutes, is performed, with a 2-minute interval before each task. CBFV is recorded bilaterally from the middle cerebral arteries using TCD during performance. A baseline CBFV measure is taken prior to each task, while the participant views a blank screen with no performance imperative. |
| 35-50 mins | DSSQ and CITS (assessment of coping), and saliva sample |
| 50-55 mins | Practice of cognitive vigilance task |
| 55-95 mins | Performance of vigilance task. CBFV is recorded during performance. |
| 95-105 mins | DSSQ and CITS |

## Results and Discussion

Results are divided into three sections: (1) manipulation checks, (2) reliability and validity of individual differences in CBFV, and (3) predictors of performance.

*Manipulation Checks*

*Subjective state response.* Figure 1 represents standardized change scores, compared to baseline, for the three DSSQ secondary factors following the short battery (left panel) and following vigilance (right panel). The data confirm that the task stressors induced subjective responses as expected. The short battery elevated distress without affecting engagement, whereas the longer vigilance task produced a large-magnitude decline in engagement, accompanied by increased distress.

*Workload.* Figure 2 shows workload ratings on the six scales of the modified NASA-TLX (0-10 scales). Ratings for the short battery (left panel) confirm that workload ratings for all scales were high, with the exception of physical demands. The highest ratings were for mental and temporal demands. Workload ratings for the vigilance task (right panel) were also high for all scales except physical demands. Workload was similar to those seen for other demanding vigilance tasks, with mental demands and frustration rated as the two highest contributors to workload. Similar patterns of workload were found in the previous study of sensory vigilance (Matthews et al., 2005).

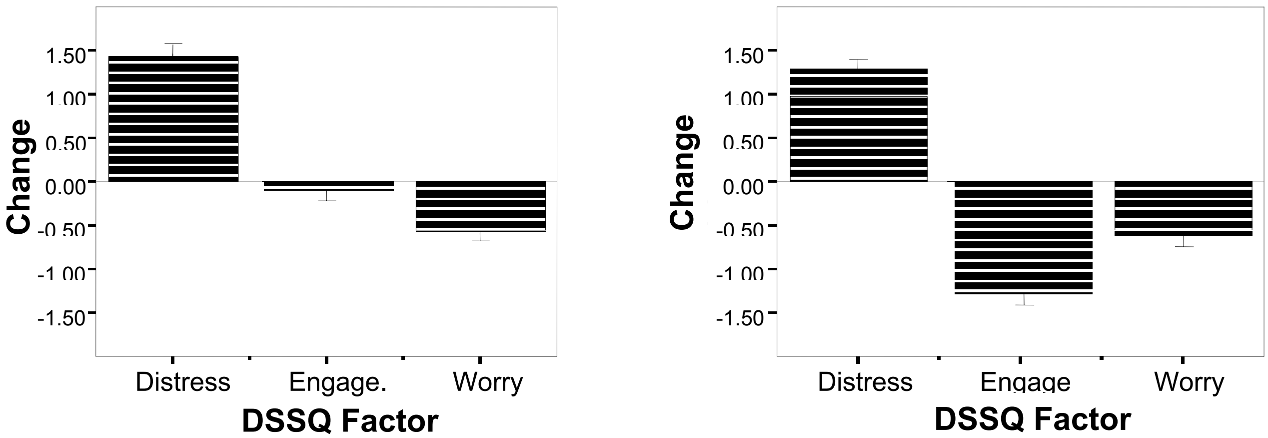



Figure 1. Task-induced change in three DSSQ factors following performance of short task battery (left panel) and vigilance (right panel). Engage. = Task Engagement. Error bars in this and subsequent figures are standard errors.

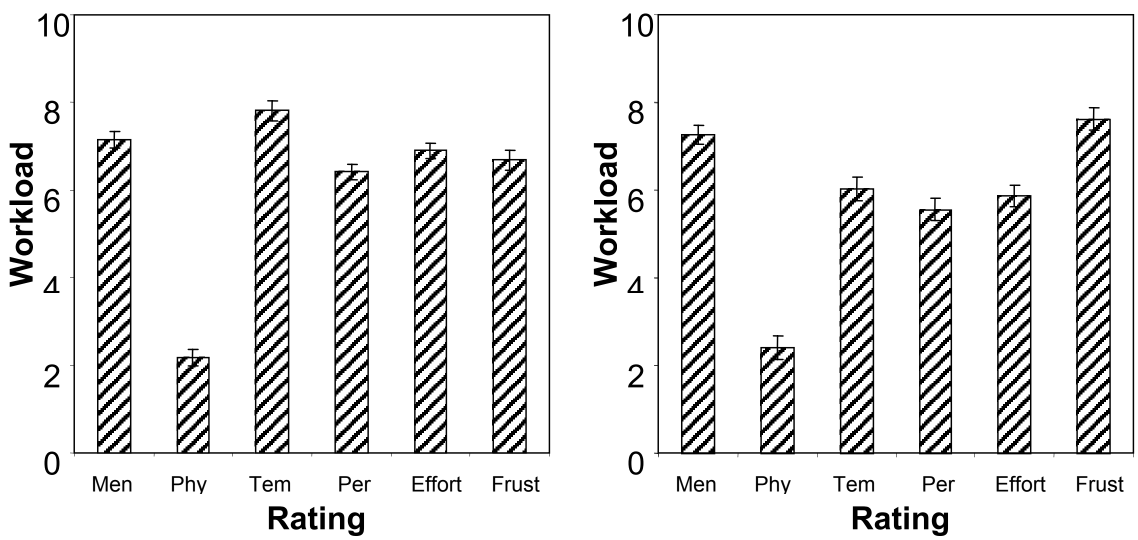



Figure 2. Workload ratings for short battery of tasks (left panel) and vigilance (right panel). Scales are Mental Demand (Men), Physical Demand (Phy), Temporal Demand (Tem), Performance (Per), Effort and Frustration (Frust).

*Vigilance performance data.* Vigilance performance data were calculated for four successive 9-min periods. One-way ANOVAs, with task period as a within-subjects factor (4 levels), were performed to test for temporal change in (1) detection rate and (2) false alarm rate. Box's epsilon was used in calculating degrees of freedom for repeated measures factors to correct for violations of the sphericity assumption (Maxwell & Delaney, 2004). There were significant effects of task period on both detections, $F(3,318) = 5.03$, $p<.01$), and false alarms, $F(3,318) = 10.54$, $p<.001$), as shown in Figure 3. As expected, a vigilance decrement showing a temporal decline in detection rate was obtained. However, by contrast with previous sensory vigilance data (Matthews et al., 2005), false alarms *decreased* over time. The data are suggestive of an increase in response criterion over time. The task was also more difficult in absolute terms than the sensory vigilance task with a lower overall detection rate and a higher false alarm rate. A further analysis was run to check temporal decrement in A', an index of perceptual sensitivity that makes fewer assumptions than the *d*' index derived from signal detection theory. An arcsine transform was used to reduce skew in A'. There was no significant effect of task period on A'. Values for the four successive periods were 0.81, 0.80, 0.80, and 0.82, respectively.

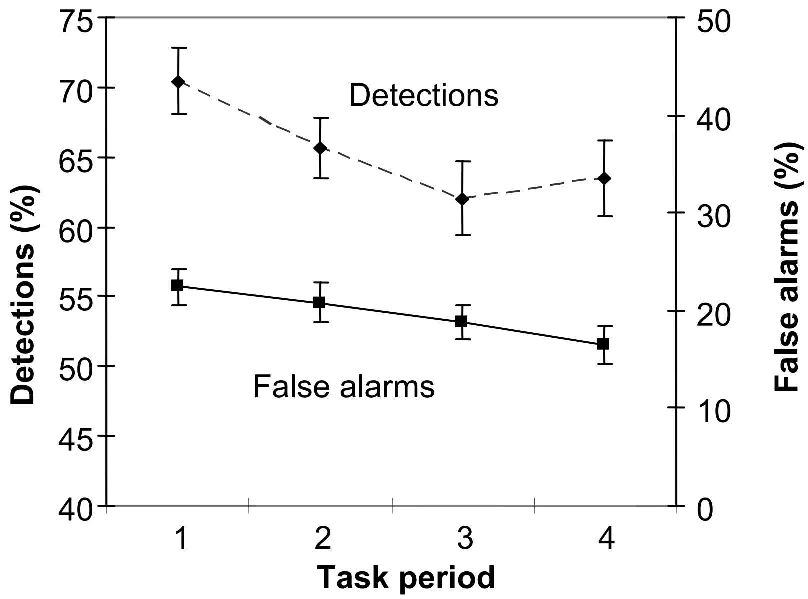



Figure 3. Correct detections (%) and false alarms (%), in four 9-minute task periods.

*Individual differences in CBFV*

This section summarizes analyses of the reliability and validity of the different CBFV indices taken during the experiment (i.e., baseline, phasic response to short tasks, CBFV during vigilance). *N*s for these analyses vary, primarily because in some participants the TCD signal was lost during recording on one or both sides due to the length of the study.

*Reliability of measurement.* The procedures used for measuring magnitude of the phasic response to performing the short task battery are described and justified in our Year 1 Report (Matthews, Warm, & Washburn, 2004). The response magnitude for each task was calculated as the percentage change in mean CBFV relative to the initial baseline assessment of bloodflow

prior to performance of any tasks. Findings were similar to those reported for the previous study, so an abbreviated account is provided here.

Table 1 shows the correlations between the phasic response indices for each of the tasks of the short battery. As in the previous study of sensory vigilance, indices were generally positively correlated, indicating a consistent individual difference in response to high workload. Inter-hemispheric correlations were higher than intra-hemispheric correlations, justifying separate calculations of mean CBFV in the left and right hemispheres. Alpha coefficients for the two indices were 0.79 (left-hemisphere; 3 observations) and 0.79 (right-hemisphere; 3 observations). The correlation between these two measures was 0.40 ($p$<.01).

Several other features of the initial study were replicated (Matthews et al., 2004, 2005). CBFV values during the four periods of work for the vigilance task were calculated as percentage changes from baseline. These CBFV measures were highly intercorrelated within left and right hemispheres (range of *r*s: - .709 - .886). They were also moderately positively correlated with the phasic response indices for the same hemisphere (range of *r*s: - .349 - .614). Hence, phasic increases were predictive of higher CBFV during vigilance. Cross-hemisphere correlations were of smaller magnitudes. In addition, the CBFV indices for the short battery and for the vigilance task were not significantly correlated with baseline CBFV levels, confirming that indices of task-induced response are unrelated to baseline bloodflow.

Table 1. Intercorrelations of phasic bloodflow indices, for each hemisphere. Tasks: Lines = line length discrimination, WM = working memory, Track = tracking, -P = phasic response index.

| | | | Left Hemisphere | | | Right Hemisphere | | |
|---|---|---|---|---|---|---|---|---|
| | | | Lines-P | WM-P | Track-P | Lines-P | WM-P | Track-P |
| Left Hemisphere | Lines-P | *r* | - | | | | | |
| | | *N* | | | | | | |
| | WM-P | *r* | .600** | - | | | | |
| | | *N* | 89 | | | | | |
| | Tracking-P | *r* | .552** | .589** | - | | | |
| | | *N* | 89 | 90 | | | | |
| Right Hemisphere | Lines-P | *r* | .390** | .262* | .322** | - | | |
| | | *N* | 76 | 76 | 77 | | | |
| | WM-P | *r* | .156 | .322** | .245* | .433** | - | |
| | | *N* | 74 | 74 | 75 | 82 | | |
| | Tracking-P | *r* | .221 | .250* | .375** | .572** | .659** | - |
| | | *N* | 76 | 76 | 77 | 84 | 82 | |

*Note.* * $p$ < .05, ** $p$ < .01

*Validity of bloodflow measurement.* As before (Matthews et al., 2005), we conducted two tests of validity. First, we tested whether the magnitude of phasic response should be lateralized, depending on the information-processing demands of the tasks, in line with previous findings (e.g., Stroobant & Vingerhoets, 2000). Second, we tested whether CBFV during

performance of the longer vigilance task showed temporal decline, as in previous sensory vigilance studies (e.g., Hitchcock et al., 2003).

*Effects of task type and hemisphere on phasic CBFV response.* The effects of CBFV and hemisphere on the task-induced phasic response are shown in Figure 4. A 3 x 2 (task x hemisphere) ANOVA, with repeated measures on both factors, demonstrated a significant main effect of task type, $F(2,146) = 14.66$, $p<.001$, and a significant task x hemisphere interaction $F(2,134) = 3.88$, $p<.05$. As reported by Stroobant and Vingerhoets (2000), CBFV tended to increase during task performance, relative to baseline. The two nonverbal tasks showed stronger right than left hemisphere responses, whereas responses to the (verbal) working memory task showed the opposite trend. By comparison with the equivalent data reported by Matthews et al. (2005), the tracking task was more strongly lateralized, and the working memory task less strongly lateralized, although the patterns of response in the two studies are qualitatively similar.

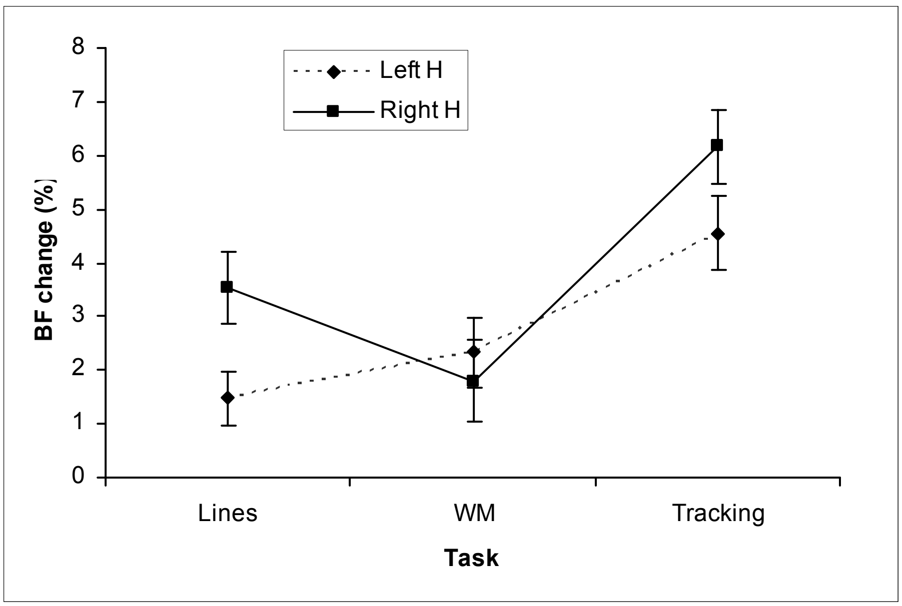



Figure 4. Phasic bloodflow response (% baseline) as a function of task type and hemisphere. Lines = line length discrimination, WM = working memory.

*Effects of task period on CBFV during vigilance.* Figure 5 shows bloodflow as a function of 9-minute task period and hemisphere. A 2 x 4 (hemisphere x period) repeated measures ANOVA showed a significant period main effect, $F(3,198) = 12.31$, $p < .01$, and a hemisphere x period interaction, $F(3,198) = 2.70$, $p < .05$.. CBFV declined across the four periods of the vigil, but the decline in CBFV was more pronounced in the RH. The pattern of temporal change is similar to that found for sensory vigilance by Matthews et al. (2005), but in that study the trend towards a hemisphere x period interaction was non-significant.

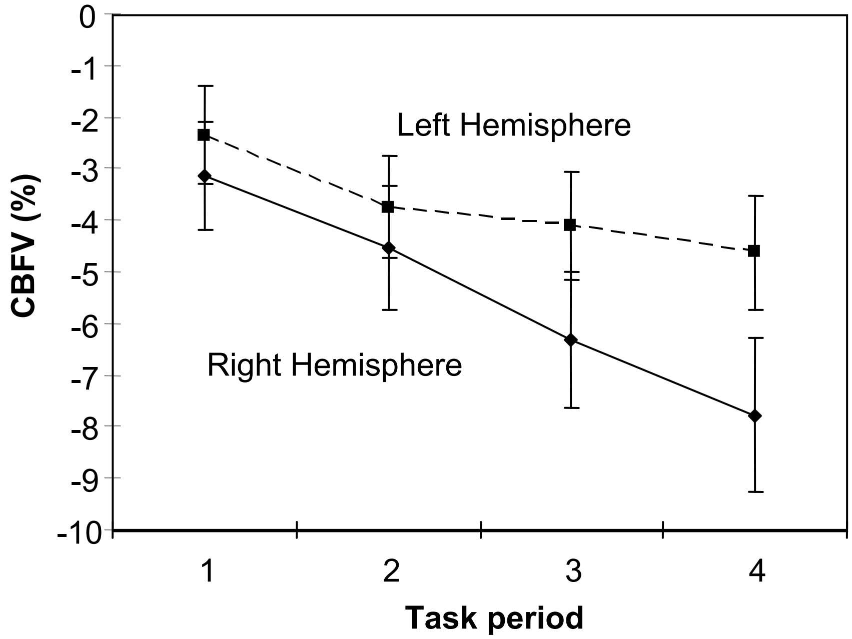



Figure 5. Cerebral bloodflow velocity (% baseline) during task performance as a function of 9-minute task period and hemisphere.

*Predictors of vigilance performance*

*Correlations between subjective measures and performance.* By contrast with the previous study (Matthews et al., 2005), subjective state variables, assessed by the DSSQ, did not correlate at more than chance levels with the phasic CBFV indices. However, performance correlates of state were similar to those seen previously. Table 4 shows how indices of vigilance performance correlated with the state factors of the DSSQ, measured following the short battery and also following the vigilance task. Correlations are given for the first and last periods of the task. Correlations based on the post-short battery measures indicate the utility of the DSSQ as a predictor of *future* sustained performance. Correlations based on the post-vigilance administration of the DSSQ are cross-sectional, but may provide further insights into the stress factors contributing to individual differences in performance. The table shows the correlations calculated separately for correction detection rate, false positive rate, and perceptual sensitivity (A').

As in the sensory vigilance study (Matthews et al., 2005; Reinerman et al., 2006), task engagement was the only reliable predictor of future detections; those individuals who were most engaged during the short task battery detected more targets on the cognitive vigilance task. Task engagement was also reliably predictive of a lower false positive rate and higher overall perceptual sensitivity (A'). Surprisingly, distress during the short battery also predicted higher A', an effect that seemed to be driven by the association between distress and a lower false alarm rate. The cross-sectional correlations showed that all three state factors related to hits and to A',

although not to false alarms. Superior vigilance was associated with higher engagement (especially towards the end of the task) and with lower distress and worry.

Table 4. Correlations between DSSQ factors and indices of vigilance during four 9-minute task periods.

| Assessment | | Task Engagement | | Distress | | Worry | |
|---|---|---|---|---|---|---|---|
| | | Period 1 | Period 4 | Period 1 | Period 4 | Period 1 | Period 4 |
| *Hits* | | | | | | | |
| Post-task (short battery) | *r* | .196* | .243* | .096 | .053 | .100 | .042 |
| Post-task (vigilance) | *r* | .153 | .399** | -.213* | -.269** | -.256** | -.286** |
| *False alarms* | | | | | | | |
| Post-task short battery) | *r* | -.256** | -.203* | -.128 | -.234* | -.054 | -.030 |
| Post-task (vigilance) | *r* | -.147 | -.052 | .179 | .079 | .108 | .063 |
| *A' (perceptual sensitivity)* | | | | | | | |
| Post-task short battery) | *r* | .240* | .322** | .218* | .233* | .042 | -.004 |
| Post-task (vigilance) | *r* | .191 | .291** | -.220* | -.227* | -.282** | -.219* |

*Note.* * $p < .05$, ** $p < .01$

A similar set of correlations was computed to test the relationships between coping strategies, as measured by the CITS, and vigilance performance, as shown in Table 5. Coping measured following the short task battery was rather inconsistently predictive of vigilance performance, but avoidance predicted fewer hits on the vigilance task and task-focus predicted fewer false alarms. The cross-sectional correlations were more robust, and both high task-focus and low avoidance were quite substantially correlated with higher perceptual sensitivity on the vigilance task.

Table 5. Correlations between CITS (coping) scales and indices of vigilance during four 9-minute task periods.

| Assessment | | Task-Focus | | Emotion-Focus | | Avoidance | |
|---|---|---|---|---|---|---|---|
| | | Period 1 | Period 4 | Period 1 | Period 4 | Period 1 | Period 4 |
| *Hits* | | | | | | | |
| Post-task (short battery) | *r* | .060 | .121 | .060 | .074 | -.236* | -.350** |
| Post-task (vigilance) | *r* | .251* | .490** | -.195* | -.101 | -.365** | -.594** |
| *False alarms* | | | | | | | |
| Post-task (short battery) | *r* | -.267** | -.196* | -.124 | -.075 | .124 | -.032 |
| Post-task (vigilance) | *r* | -.363** | -.231* | .126 | .070 | .303** | .092 |
| *A' (perceptual sensitivity)* | | | | | | | |
| Post-task (short battery) | *r* | .117 | .210* | .089 | .073 | -.183 | -.173 |
| Post-task (vigilance) | *r* | .370** | .436** | -.207* | -.153 | -.414** | -.420** |

*Note.* * $p < .05$, ** $p < .01$

*Trait predictors.* The sensory vigilance study failed to find any reliable personality predictors of vigilance in relation to the Five Factor Model of personality. The present data also indicated that personality traits are at best weakly predictive of the task. Some significant correlations were found. For example, hits in period 1 correlated at .28 ($p$<.01) with agreeableness and at -.31 ($p$<.01) with neuroticism. At period 4, hits were significantly negatively correlated with extraversion at -.22 ($p$<.05). However, none of these correlations remained robust across task periods and none of the Five Factor Model traits was significantly correlated with A' in period 4. By contrast, as shown in Table 6, reasoning ability was reliably positively correlated with more accurate response and higher A' throughout the vigil. Reasoning ability also correlated positively to a moderate degree with some of the other predictor variables measured following the short task battery including task engagement ($r$ = .33, $p$<.01), task-focused coping ($r$ = .24, $p$<.05), and right hemisphere CBFV ($r$ = .24, $p$<.05). It is unclear whether the state associated with these variables enhances ability test performance, or whether more intelligent individuals are more energized by the demands of the task.

Table 6. Correlations between ability and indices of vigilance during four 9-minute task periods.

| | Hits | | False Alarms | | A' | |
|---|---|---|---|---|---|---|
| | Period 1 | Period 4 | Period 1 | Period 4 | Period 1 | Period 4 |
| *r* | .267** | .319** | -.585** | -.511** | .515** | .542** |

*Note.* ** $p < .01$

*Correlations between CBFV and performance.* Table 7 gives correlations between the phasic CBFV measures and vigilance performance indexed in terms of correct detections, false alarms, and perceptual sensitivity (A’) at periods 1 and 4. In general, as expected, higher CBFV response to the short tasks predicted a higher rate of detections, a lower rate of false alarm responses, and higher A’. Left hemisphere CBFV was more predictive of correct detections and right hemisphere response of false alarms, a pattern also seen in the sensory vigilance study. Both hemispheres correlated positively with A’, especially in period 4.

The data also allow a test of whether relationships between phasic CBFV and vigilance are task-specific or generalize across the different task types that elicit increased CBFV. Task-specificity implies that CBFV during the short working memory task should be the index most predictive of the cognitive vigilance task because it was designed to impose a substantial working memory load. In fact, differences between the correlations obtained with the three different task components of the short task battery were minor and the best prediction was obtained using the measures of mean CBFV, averaged across the three tasks.

Table 7. Correlations between phasic bloodflow indices and three indices of vigilance performance during the first and fourth task periods.

| | | | Detections | | False Alarms | | A’ | |
|---|---|---|---|---|---|---|---|---|
| | | | Period 1 | Period 4 | Period 1 | Period 4 | Period 1 | Period 4 |
| Left Hemi. | Lines-P | *r* | .207* | .298** | .003 | -.004 | .121 | .234* |
| | | *N* | 88 | 88 | 88 | 88 | 86 | 83 |
| | WM-P | *r* | .190 | .207* | -.204 | -.221* | .245* | .309** |
| | | *N* | 89 | 89 | 89 | 89 | 87 | 84 |
| | Tracking-P | *r* | .225* | .096 | -.161 | -.171 | .288** | .186 |
| | | *N* | 90 | 90 | 90 | 90 | 88 | 85 |
| | Left-P (mean) | *r* | .247* | .220* | -.147 | -.159 | .267* | .275* |
| | | *N* | 88 | 88 | 88 | 88 | 86 | 83 |
| Right Hemi. | Lines-P | *r* | .053 | .235* | -.258* | -.282** | .176 | .392** |
| | | *N* | 83 | 83 | 83 | 83 | 82 | 79 |
| | WM-P | *r* | .043 | .091 | -.230* | -.284* | .163 | .285* |
| | | *N* | 81 | 81 | 81 | 81 | 80 | 78 |
| | Tracking-P | *r* | .104 | .150 | -.213 | -.195 | .204 | .280* |
| | | *N* | 83 | 83 | 83 | 83 | 82 | 79 |
| | Right-P (mean) | *r* | .072 | .140 | -.266* | -.315** | .201 | .368** |
| | | *N* | 81 | 81 | 81 | 81 | 80 | 78 |

*Note.* * $p < .05$, ** $p < .01$

The sensory vigilance study failed to find any significant associations between vigilance and CBFV measured concurrently with performance. In the present data, concurrent CBFV was similarly not predictive of hits and false alarms. However, some CBFV correlates of A' were found when A' was used as the performance index, as shown in Table 8. In the first task period, CBFV in both hemispheres correlated positively with A', but the correlations drop to non-significance in the later stages of the task.

Table 8. Concurrent correlations between CBFV and A' on the vigilance task during four successive task periods.

| Hemisphere | | Period-1 | Period-2 | Period-3 | Period-4 |
|---|---|---|---|---|---|
| Left | *r* | .247* | .118 | .213 | .084 |
| | N | 83 | 83 | 82 | 80 |
| Right | *r* | .293** | .343** | .179 | .127 |
| | N | 77 | 77 | 75 | 72 |

*Note.* * *p* < .05, ** *p* < .01

*Regression models.* As a final analysis of the data, regression models were constructed to test whether multiple independent predictors of performance could be identified, as in the study of sensory vigilance (Matthews et al., 2005). The regressions reported for that study indicated that CBFV and subjective task engagement may predict vigilance somewhat independently, so that the prediction of performance may be enhanced by using both indices as diagnostic measures. Workload was found to operate as a moderator variable, such that CBFV was more predictive for individuals who rated workload as low.

In the present study, the phasic CBFV and DSSQ measures, recorded following the task battery, were explored as predictors of perceptual sensitivity (A') in task period 4, as the criterion for vigilance and performance. The correlational data reported above suggested that A' relates to both the DSSQ and to the CBFV indices. As a preliminary step, we tested whether workload had a similar moderator effect in the prediction of vigilance from CBFV, as in the sensory vigilance study. In this study, by contrast with the earlier one, there was a significant negative correlation between workload and A' ($r = -.305$, $p<.01$). However, adding workload × CBFV product terms to the regression equation did not add significantly to the variance explained. A further preliminary check showed that there were no gender differences in performance. Thus, the regression was performed with only the CBFV and DSSQ measures included.

A two-step hierarchical regression model was tested. The two phasic CBFV response measures were entered initially, followed by the three DSSQ factors at the second step. For the final equation, $R = .516$ ($R^2 = .216$, $F(5,68) = 4.93$, $p<.01$). Table 9 shows summary statistics. In the final equation, right-hemisphere CBFV ($\beta = 0.24$, $p <.05$) and task engagement ($\beta = 0.30$, $p <.01$) both made significant contributions to the variance explained. Similar to the sensory vigilance data, inclusion of both types of index in the equation improves prediction.

Table 9. Summary statistics for the regression of A’ (period 4) on multiple predictor variables.

| Step | Variables | Change in $R^2$ | *F* | df | Sig. |
|---|---|---|---|---|---|
| 1 | CBFV: Left-P, Right-P | .155 | 6.50 | 2,71 | $p<.01$ |
| 3 | DSSQ (Engagement, Distress, Worry) | .111 | 3.43 | 3,68 | $p<.05$ |

*Note.* Left-P, Right-P = phasic response indices for left and right hemispheres.

## Discussion

The simplest conclusion to be drawn from these findings is that there are many commonalities between the sensory and cognitive vigilance tasks investigated in the present research despite the differences in the information-processing required to detect targets. Manipulation checks confirmed that the cognitive vigilance task elicited increased subjective distress and a decline in task engagement relative to baseline, corresponding to a state of fatigue. Magnitudes of the changes in state were substantial and very similar to those elicited by the sensory vigilance task. The workload profile of sensory and cognitive tasks was also very similar. Furthermore, like the sensory vigilance task, the cognitive vigilance task produces declines in performance and CBFV comparable to those seen in previous vigilance studies (e.g., Warm & Parasuraman, 2007). These similarities were maintained despite some performance differences between the two tasks. The cognitive task was more difficult, as evidence by higher error rates and lower perceptual sensitivity (A’). Although a vigilance decrement was apparent in the data on hits, there was no change in perceptual sensitivity over the period of the watch. The difficulty of the task in the first period may have limited the scope for a further decline in A’.

Subjective and CBFV responses to the short battery resembled those seen in the earlier study (Matthews et al., 2005; Reinerman et al., 2006). At a subjective level, the short, high workload tasks elicited distress but not loss of engagement. The dependence of the CBFV response on task and hemisphere seen in the sensory vigilance study also replicated to a large degree. Individual differences in the CBFV response to the short task battery were found to be reliable and meaningfully inter-related across tasks and hemispheres. The pattern of correlations suggested both a generalized response across the two hemispheres, together with more specific intra-hemispheric responses.

Predictors of cognitive vigilance resembled those of sensory vigilance. Subjective task engagement and phasic CBFV responses to the short task battery correlated positively and significantly with subsequent cognitive vigilance performance. Data also showed that, as for sensory vigilance, conventional personality measures are of limited utility as predictors of cognitive vigilance. However, in keeping with the working memory demand of the task, a

cognitive ability test was shown to be a valid predictor. The concurrent correlations (as opposed to prediction from the measures derived from the short task battery) implicated further factors relating to individual differences in vigilance. Distress and worry during the task correlated with lower detection rates and lower A'. Coping scales measured by the CITS also correlated positively with hits, A', and negatively with false positive frequencies. The combination of high task-focus and low avoidance appears most beneficial for cognitive vigilance. By contrast with the sensory vigilance study, significant positive correlations between CBFV and A' were found in the first period of watch for both hemispheres. However, these associations dissipated over the later periods. It is possible that first period CBFV is related to the phasic responses that may be the more reliable predictors of vigilance.

At a theoretical level, the contrast between sensory and cognitive vigilance tasks raises the issue of whether resources for vigilance are unitary or multiple. For example, multiple resource theory (e.g., Wickens & Hollands, 1999) suggests that there may be separate resource pools for left and right hemispheres, implying the need for separate predictive models for tasks drawing on one or other hemisphere exclusively. Whereas the sensory task investigated in the previous study may be attributed to right hemisphere processing, the cognitive task in requiring working memory and extraction of symbolic codes (letter codes) might be expected to depend on the left hemisphere. However, temporal decline in CBFV was greater in the right than in the left hemisphere. Previous studies of CBFV concur with brain-imaging studies in localizing vigilance in the right hemisphere (Hollander et al., 2003). The present data suggest that, even with a task traditionally associated with left hemisphere functioning, vigilance may be influenced by right hemisphere neural circuits. In addition, the regression analysis indicated that right hemisphere phasic CBFV was more predictive of perceptual sensitivity than the left hemisphere index (although both indices predicted performance in the bivariate correlations). Thus, although it is likely that performance of the task recruited left-hemisphere circuits, the *energetics* of performance appear to be controlled either by right-hemisphere vigilance circuits or by a cross-hemispheric general resource. Thus, task engagement and CBFV increments may both reflect a common resource pool for "energization" of information-processing (cf., Matthews et al., 2000). The resource model is also supported by the intercorrelations of the CBFV responses to three tasks of differing information-processing characteristics. The lack of dependence of the correlations between CBFV and vigilance on the processing requirements of the screening battery tasks also supports a unitary resource model.

At a practical level, the results provide further support for using resource theory as a basis for deriving predictors of sustained cognitive performance. Assessment of the operator's response to a short cognitive challenge may provide both subjective and physiological diagnostic indicators of future performance. The regression analysis showed that, in combination, the DSSQ and CBFV measures predict around 20% of the variance in vigilance performance, corresponding to a multiple $R$ that is sufficiently large to be practically useful for selection purposes. This level of explained variation is meaningful given that vigilance failures in situations such as air-traffic control, baggage screening, and medical monitoring can be extremely costly in terms of public safety and health (Hancock & Hart, 2002; Rose et al., 2002). The $R$-squared value also exceeds that obtained using standard personality measures for which bivariate correlations rarely exceed 0.2 – 0.3 (e.g., Koelega, 1992). Taken together, the two studies of sensory and cognitive vigilance imply that subjective and psychophysiological

measures of individual differences in resource availability or utilization are of value in predicting future performance and diagnosing vulnerability to loss of vigilance.

## UC- STUDY 2: DIAGNOSTIC PREDICTORS OF SIMULATED VEHICLE DRIVING

The study of cognitive vigilance previously described (UC-Study 1) obtained similar findings to the earlier study of sensory vigilance (Matthews et al., 2004, 2005). It showed that CBFV declined through the period of watch in both hemispheres during the vigilance task. Furthermore, psychophysiological responses to the short battery of high workload tasks predicted individual differences in the subsequent cognitive vigilance task. Higher CBFV in both hemispheres, as well as subjective task engagement and use of task-focused coping predicted higher perceptual sensitivity. These results support a resource model of vigilance, consistent with previous findings (Warm, Matthews & Finomore, in press). Both hemodynamic and subjective measures of individual differences in resource availability may be useful as diagnostic predictors.

The results from U.C. thus far have been restricted to tasks requiring monitoring for critical stimuli only. However, in operational settings, monitoring must be combined with other task components. It is unclear how far findings with single vigilance tasks would generalize to such multi-task situations. The present study aimed to test the utility of monitoring CBFV in a multi-component task, simulated vehicle driving. Driver stress and fatigue are well-known to be potentially dangerous during vehicle driving (Hitchcock & Matthews, 2005). Studies using driving simulators have identified a variety of behavioral indices of fatigue, including deterioration in steering of the vehicle and mental fatigue (Matthews & Desmond, 2002; Philip, et al., 2003). Safety would be enhanced if diagnostic indices were available to predict and identify the onset of fatigue prior to behavioral impairment.

The prediction of vehicle driving was addressed in one of the studies reported in our Year 1 report (UC-Study 2: Matthews et al., 2004; see also Funke, Matthews, Warm & Emo, 2007). As discussed in the introduction to that study, over 50% of army military fatalities in FY03 were the result of motor vehicle accidents (United States Army Safety Center: https/safety.army.mil/ipr/ IPRFY03WEB2.ppt). In Iraq, convoys are a frequent target for insurgents. The driver's vigilance for improvised explosive devices (IEDs) and cues toward insurgent activity is critical for survival. The stress and fatigue often associated with convoy driving may negatively impact on vigilance. Diagnostic monitoring of the driver's vigilance is thus an avenue worth exploring.

The earlier study addressed only the utility of subjective measures in predicting sustained driver performance in a dual-task situation requiring monitoring of pedestrian stimuli. (It also investigated the role of vehicle automation, which did not feature in this study). The Driver Stress Inventory (DSI; Matthews, Desmond, Joyner, & Carcary, 1997) was used to assess traits related to vulnerability and fatigue, whereas in the vigilance studies, the DSSQ measured subjective state dimensions. Subjective data confirmed that the driving task elicited a similar stress response to the sensory and cognitive vigilance tasks; i.e., elevated distress and decreased task engagement. A stress manipulation further increased distress. Data also confirmed the utility of the DSI as a predictor of fatigue and stress states experienced during the simulated drive. Multiple regression analyses showed that the DSSQ and DSI predicted vehicle control (SD of lateral position in the lane), but not rate of detecting critical signals on the secondary task. In this instance, primary task performance was more strongly associated with the predictor variables. A

multiple regression equation showed that several state and trait factors predicted vehicle control independently; together, they added an additional 21% to the variance explained by task factors. Similar to the vigilance studies, higher task engagement was associated with better vehicle control (lower SD in lateral position). This finding suggests that the resource theory framework for vigilance may also apply to vehicle driving.

*Aims of the study*

The study aimed to test whether CBFV and subjective measures are related to vehicle driving performance during a simulated drive that was purposely designed to be monotonous and fatiguing. The battery of predictors used was derived from our earlier studies of simulated driving (Matthews et al., 2004) and vigilance (Matthews et al., 2004, 2005). The DSI and DSSQ were used to assess subjective traits and states of stress and fatigue, respectively. The same 'two-phase' protocol used in the vigilance studies was applied to the driving setting. Participants completed the short task battery prior to the simulated drive. To the extent that the general resource model applies to the simulated driving task, it may be predicted that CBFV and task engagement responses to the short task battery should be diagnostic of subsequent driving performance. Because the study aimed to induce fatigue, the simulated drive differed from the previous one (Matthews et al., 2004) in being designed to be monotonous. Loss of attention and vigilance may be a particular safety problem for vehicle drivers in monotonous conditions (Thiffault & Bergeron, 2003). The driver followed a straight road for a 36 minute period without any other traffic being present. The only additional stimuli were the pedestrian stimuli used for the secondary detection task and trees placed by the road to enhance the driver's sense of apparent motion.

## Method

The general method for the series of studies is reported by Matthews et al. (2004). This study follows the same protocol, but with a simulated driving task in place of the vigilance task. Here, we report a summary of the method. The reader should refer to Matthews et al. (2004) for details of the method not described below.

*Participants*

There were 68 participants, recruited from UC introductory psychology students, of whom 58% were female. Mean age was 20.6. Inclusion and exclusion criteria are listed in Matthews et al. (2004). An additional inclusion criterion was that the participant should hold a valid driver's license.

*Experimental Design*

All subjects performed the same simulated drive. Dependent variables included subjective measures of post-task subjective state, coping, and workload assessed by the DSSQ and CITS questionnaires and objective measures of task performance obtained through the driving simulator.

*Psychophysiological indices*

A Nicolet Companion III TCD unit with two ultrasound transducers fitted within a head bracket was used to record CBFV in the medial cerebral arteries bilaterally. Previous studies at the University of Cincinnati (e.g., Hitchcock et al., 2003; Warm & Parasuraman, 2007) have shown that decreases in CBFV are linked to loss of sustained attention.

Salivary cortisol may index the activation of a hypothalamic-pituitary-adrenal axis (HPA), corresponding to the well-known 'fight-or-flight' response (e.g., Dickerson & Kemeny, 2004). Saliva was assayed by having participants chew on a cotton 'Salivette', that was sent to an external laboratory for analysis. These data, however have not been received from the laboratory as of yet, and so are not reported here.

*Questionnaires*

*Stress vulnerability*. The Driver Stress Inventory (DSI: Matthews, Desmond, Joyner, & Carcary, 1997) is an experimentally validated questionnaire designed to assess an individual's vulnerability to stress in a driving context, and to evaluate the coping methods typically employed in stressful driving situations. It is comprised of 41 items designed to assess a driver on five dimensions of driver-stress vulnerability: aggression, dislike of driving, hazard monitoring, thrill seeking, and fatigue proneness. DSI scores are scaled so that they range from 0-100.

*Subjective states, coping, and workload.* The Dundee Stress State Questionnaire (DSSQ: Matthews et al., 1999, 2002) assesses participants' immediate moods, motivations, cognitions, and coping strategies prior to or following task performance. It may be scored for three broad subjective state factors: task engagement, distress, and worry. The post-task version also includes a short workload assessment, based on the NASA-TLX (Hart & Staveland, 1988). The Coping Inventory for Stressful Situations (CITS: Matthews & Campbell, 1998) assesses task-focused, emotion-focused, and avoidance coping in the specific context of task performance.

*Driving Simulator and Performance Tasks*

The simulator used was a Systems Technology, Inc. simulator. The simulator was fully programmable, allowing it to be used to measure performance in a variety of driving contexts. The traffic scene for the simulated drive was projected onto three screens by three separate MultiSync VT 540 projectors. The simulator was equipped with full sized gas and brake pedals and a steering wheel capable of 360 degree steering, which supplied realistic resistance by means of a computer controlled torque motor.

Participants initially completed a 5.5-minute practice drive designed to allow them to become accustomed to the simulator and to practice the secondary hazard monitoring task. During this task, pedestrians were lined up on both sides of the roadway. As the driver approached, the pedestrian would either remain stationary or begin moving towards the driver without walking into the roadway. Moving pedestrians constituted the critical signal. The driver was required to respond to critical signals by using the turn signal, indicating right on the turn signal for pedestrians on the right side of the road or left on the turn signal for pedestrians on the left side of the road. Participants had six seconds to detect and respond to the moving pedestrians (five seconds before the participant passed the pedestrian, and one second after they passed the

pedestrian). The computer was programmed to record the participant's reaction time and response to each moving pedestrian (correct, incorrect, and no response). Participants were instructed to drive at 35 M.P.H. on the right side of the road at all times. During the main experiment, 320 pedestrians were presented and were balanced for the side of the road they were on. At a driving speed of 35 M.P.H. (the posted speed limit), this equals a presentation rate of ten pedestrians per minute. Of those ten, two were critical signals, yielding a total of 64 critical signals in the experiment. The main driving task was programmed to stop following 34.5 minutes or after the participant traveled 106,260 feet (which also equals 34.5 minutes at 35 M.P.H.)..

A pilot study showed that the apparatus was working correctly and drivers were able to respond to the critical signals using the turn signal. Unfortunately, following conclusion of the study, it was found that a mechanical failure in the turn signal indicator had prevented the turn signal data from being recorded for most of the subjects. Thus, no data on hazard detection are presented here. Data on vehicle control were recorded correctly and were analyzed.

### *Procedure*

The sequence of assessments and tasks was as follows:

| *Time* | *Assessment* |
|---|---|
| 0-5mins | Driver Stress Inventory for traits related to stress vulnerability |
| 5-20 mins | Pre-task DSSQ (assessment of subjective state) and saliva sample (stored and later assayed for cortisol) |
| 20-35 mins | A short battery of three demanding tasks, each lasting 2 minutes, is performed with a 2-minute interval before each task. CBFV is recorded bilaterally over the middle cerebral arteries using TCD during performance. A baseline CBFV measure is taken prior to each task, while the participant views a blank screen with no performance imperative. |
| 35-50 mins | Post-task DSSQ (subjective state and workload) and CITS (coping) and saliva sample |
| 50-55 mins | Practice of simulated driving task |
| 55-91 mins | Performance of, simulated driving requiring vehicle control and detection of secondary task stimuli. CBF is recorded during performance. |
| 91-101 mins | Post-task DSSQ and saliva sample |

## Results and Discussion

Results are divided into three sections: (1) manipulation checks, (2) reliability and validity of individual differences in bloodflow, and (3) predictors of performance

### *Manipulation Checks*

*Subjective state response.* Figure 1 represents standardized change scores, compared to baseline, for the three DSSQ secondary factors following the short battery (left panel) and following simulated driving (right panel). As in previous studies, the short battery elevated distress without affecting engagement. The simulated driving task produced a large-magnitude decline in engagement, accompanied by a large elevation of distress and a smaller decline in worry. This pattern of state change is similar to that elicited by the sensory and cognitive vigilance tasks, although the magnitude of state change was a little smaller than that seen in previous studies. Hence, the driving task was effective in producing a fatigued mental state corresponding to those seen in the vigilance studies.

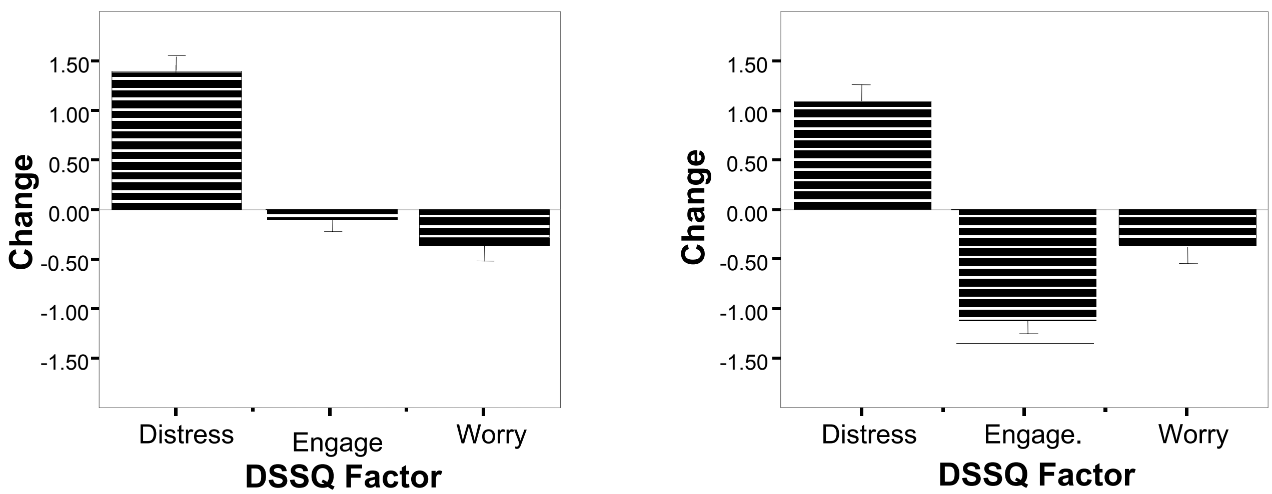



Figure 1. Task-induced change in three DSSQ factors following performance of short task battery (left panel) and simulated driving (right panel). Engage. = Task Engagement. Error bars in this and subsequent figures are standard errors.

*Workload.* Figure 2 shows workload ratings on the six scales of the modified NASA-TLX (0-10 rating scales). Ratings for the short battery (left panel) once again confirm that workload ratings for all scales were high with the exception of physical demands. The highest ratings were for mental and temporal demands. Workload ratings for the simulated task (right panel) were substantial, but the pattern of ratings differed somewhat from that seen for sensory and cognitive vigilance. Mental demands, temporal demands, and performance workload were all 1-2 points lower than the ratings obtained for vigilance, although stress continued to be

highly rated. Physical demands were higher than for vigilance, reflecting the motor demands of vehicle steering.

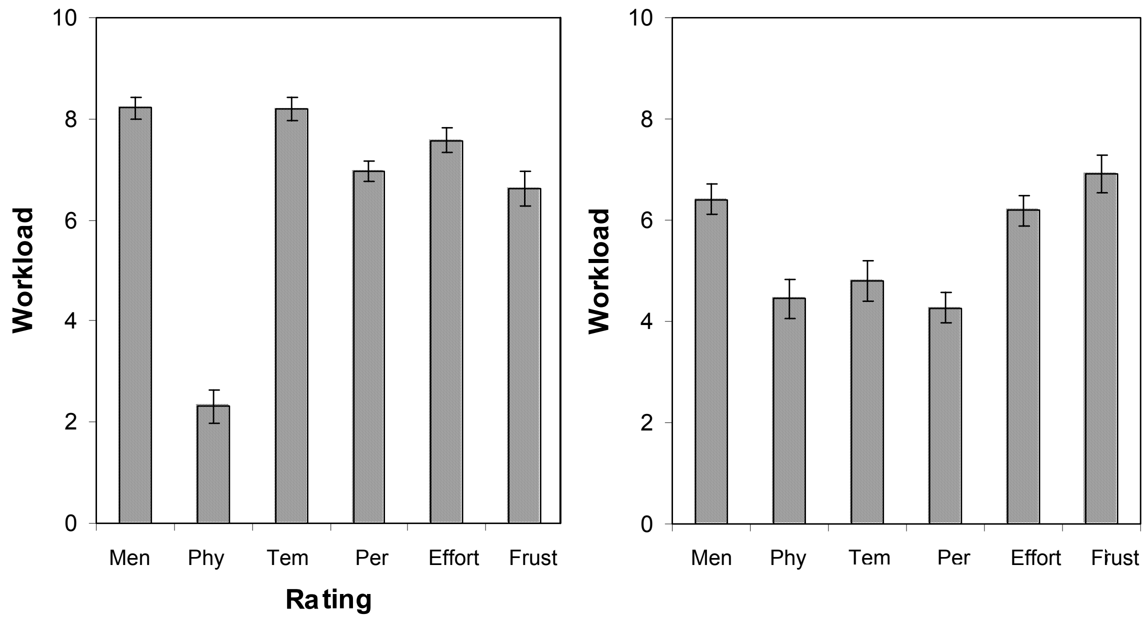



Figure 2. Workload ratings for short battery of tasks (left panel) and simulated driving (right panel). Scales are Mental Demand (Men), Physical Demand (Phys), Temporal Demand (Temp), Performance (Perf), Effort and Frustration (Frust).

*Driver performance data*

Two performance measures were taken from the driving simulator, both of which were averaged across successive 9-min periods. The first was the standard deviation (SD) of the driver's lateral position with respect to the center line on the road. This measure provides an index of the driver's control and steering of the vehicle; a high SD indicates that the vehicle is veering from side to side on the road. The second measure was the speed of the vehicle in M.P.H. One-way ANOVAs, with task period as a within-subjects factor (4 levels), were performed to test for temporal change in (1) SD of lateral position and (2) mean speed. Box's epsilon was used when appropriate in calculating degrees of freedom for repeated measures factors to correct for violations of the sphericity assumption (Maxwell & Delaney, 2004). There was a significant effect of task period on SD of lateral position, $F(3,201) = 13.97$, $p<.01$. With Box's correction applied, the effect of task period on speed was close to significance ($F(3,201) = 3.42$, p=.054), as shown in Figure 3. Both variability in position and speed tended to increase over time.

The Figure also shows that variance in speed within each block of trials increased with task period. In the first period, most participants complied with the instruction to drive at 35 M.P.H.and the standard error is consequently low. In later periods, especially in periods 3 and 4, there was a more pronounced individual variability in speed. The increase in SD of lateral position suggests a temporal decrement in performance. One may wonder whether the increase

in SD was a consequence of increasing speed. The correlation between SD of lateral position and speed was significant only at period 3 ($r$ = .334, $p$<.01). The range of $r$s at the other periods were -.157 and - .161. Thus, changes in vehicle control did not appear to be entirely dependent on speed.

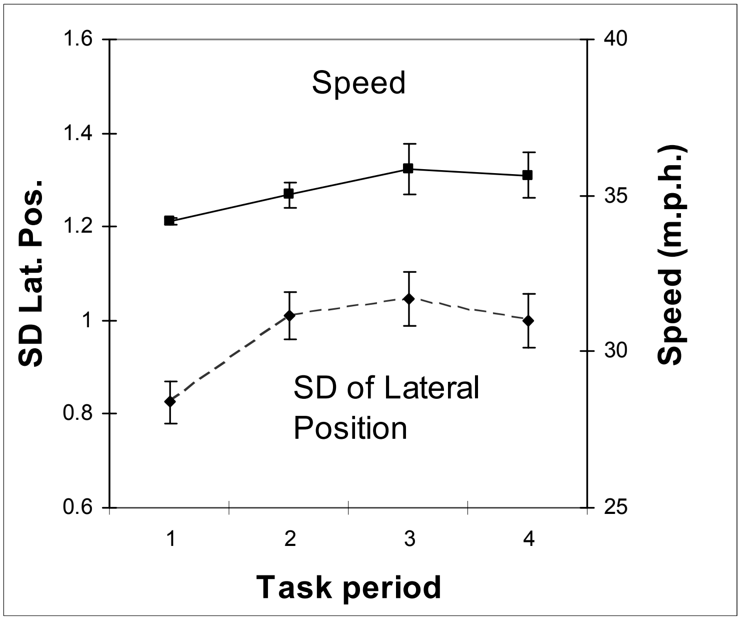



Figure 3. SD of lateral position and mean speed (m.p.h.) as a function of four 9-minute task periods.

*Individual differences in bloodflow*

This section summarizes analyses of the reliability and validity of the different CBFV indices taken during the experiment (i.e., baseline, phasic response to short tasks, CBFV during vigilance). *N*s for these analyses vary, primarily because in some participants the TCD signal was lost on one or both sides during recording due to the length of the study.

*Reliability of measurement.* The procedures used for measuring magnitude of the phasic response to performing the short task battery are described and justified in our Year 1 Report (Matthews, Warm, & Washburn, 2004). The response magnitude for each task was calculated as the percentage change in mean CBFV, relative to the initial baseline assessment of CBFV, prior to performance of any tasks. Findings were similar to those reported for the short battery employed in the studies of sensory and cognitive vigilance, so only a brief account is given here.

Cerebral bloodflow velocity responses were inter-correlated as in the previous studies. Table 1 shows the correlations between the phasic response indices for each of the tasks of the short battery. As before, indices are generally positively correlated, indicating a consistent individual difference in response to high workload. Intra-hemispheric correlations were higher than inter-hemispheric correlations, so that, again, mean CBFV was calculated separately in the left and right hemispheres. Fewer cross-hemisphere correlations attained significance in this

study compared to previous ones, but this result may be attributable to the lower sample size. The alpha coefficient for the left-hemisphere of .652 was lower than in previous studies, but the right-hemisphere alpha of .797 was similar to previous results. The correlation between the averaged left and right hemisphere measures was 0.25 ($.05<p<.10$).

Table 1. Intercorrelations of phasic bloodflow indices, for each hemisphere. Tasks: Lines = line length discrimination, WM = working memory, Track = tracking, -P = phasic response index.

| | | | Left Hemisphere | | | Right Hemisphere | | |
|---|---|---|---|---|---|---|---|---|
| | | | Lines-P | WM-P | Track-P | Lines-P | WM-P | Track-P |
| Left Hemisphere | Lines-P | *r* | - | | | | | |
| | | *N* | | | | | | |
| | WM-P | *r* | .294* | - | | | | |
| | | *N* | 59 | | | | | |
| | Tracking-P | *r* | .565** | .287* | - | | | |
| | | *N* | 59 | 59 | | | | |
| Right Hemisphere | Lines-P | *r* | .291* | .078 | .152 | - | | |
| | | *N* | 53 | 53 | 53 | | | |
| | WM-P | *r* | .008 | .168 | .045 | .698** | - | |
| | | *N* | 53 | 53 | 53 | 58 | | |
| | Tracking-P | *r* | .334* | .172 | .219 | .536** | .501** | - |
| | | *N* | 53 | 53 | 53 | 58 | 59 | |

*Note.* * $p < .05$, ** $p < .01$

CBFV values during the four periods of simulated driving were calculated as percentage changes from baseline. As in vigilance studies, these CBFV measures were highly intercorrelated within left and right hemispheres (range of *r*s: - .778 - .960) and more moderately correlated across hemispheres (range of *r*s: .232 - .415), implying some degree of cerebral differentiation of response. The phasic increases seen in response to the short battery were also predictive of higher CBFV during vigilance, especially within the same hemisphere.

*Validity of bloodflow measurement.* The effects of bloodflow and hemisphere on the task-induced phasic response are shown in Figure 4. Effects were analyzed within 3 x 2 (task x hemisphere) ANOVA, with repeated measures on both factors. A significant main effect of task type was obtained, $F(2,104) = 10.79$, $p<.01$, and also a significant task x hemisphere interaction, $F(2,134) = 6.25$, $p<.01$. The pattern of CBFV response was broadly similar to that seen in the prior vigilance studies. Tracking elicited the strongest response, and the line length discrimination task showed the strongest lateralization, in favor of the right hemisphere. However, in these data, the left hemisphere responses to the lines and working memory tasks are a little weaker than those seen in previous studies.

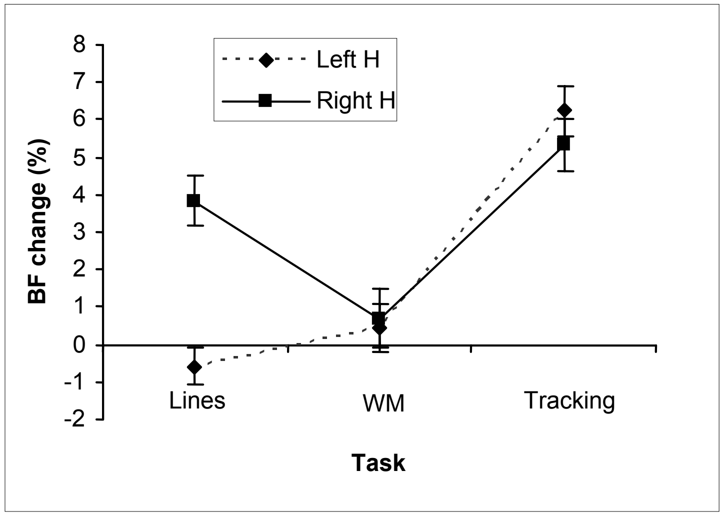



Figure 4. Phasic bloodflow response (% baseline) as a function of task type and hemisphere. Lines = line length discrimination, WM = working memory.

*Effects of task period on CBFV during vehicle driving.* Figure 5 shows bloodflow as a function of 9-minute task period and hemisphere. A 2 x 4 (hemisphere x period) repeated measures ANOVA showed a significant period main effect, $F$ (3,132) = 20.61, $p < .01$, but there was no significant main or interactive effect of hemisphere. As with the vigilance tasks, there was a progressive decline in CBFV over time evident in both hemispheres.

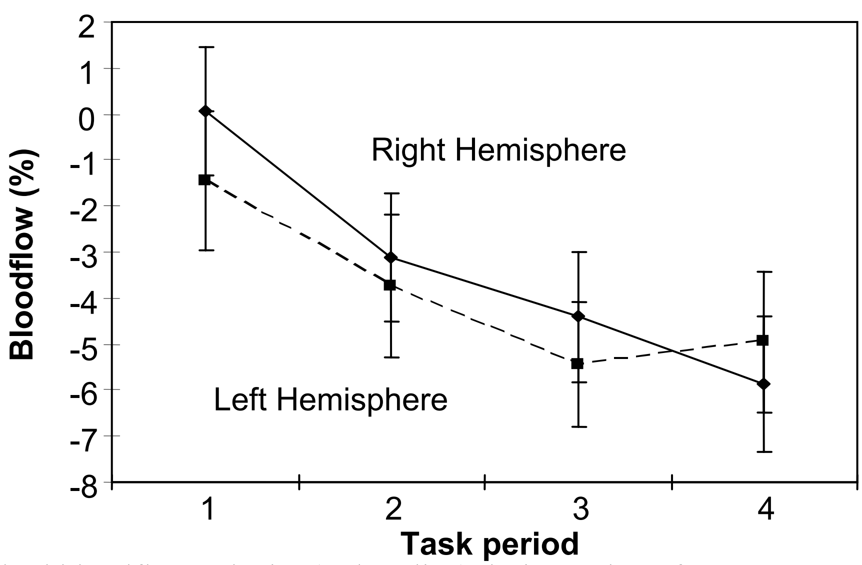



Figure 5. Cerebral bloodflow velocity (% baseline) during task performance as a function of 9-minute task period and hemisphere.

*Predictors of driving performance*

Correlations were calculated between the two performance indices – SD of lateral position and mean speed – and the subjective and CBFV measures. Some significant associations between the CBFV measures and subjective states were obtained. The right hemisphere CBFV response to the short task battery correlated positively and significantly with task engagement, both as measured following the task battery ($r$ = .262, $p$<.05) and following the drive ($r$ = .313, $p$<.05). Data from the sensory vigilance study also showed a positive association between phasic CBFV response and task engagement. DSSQ measures taken following the drive and measuring the subjective state experienced during the drive, correlated with right-hemisphere CBFV during the drive. No left-hemisphere CBFV correlates of the DSSQ were found. Table 2 shows the right-hemisphere correlations. Higher task engagement and lower worry tended to be associated with higher CBFV throughout the drive.

Table 2. Correlations of left hemisphere CBFV with subjective state factors, across four 9-minute task periods.

.

| DSSQ factor | | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|---|
| Distress | *r* | .027 | -.035 | -.105 | -.076 |
| Engagement | *r* | .279* | .338* | .250 | .309* |
| Worry | *r* | -.159 | -.313* | -.242 | -.265* |

*Note.* * *p* < .05, ** *p* < .01

However, by contrast with the vigilance studies, few correlates of the performance measures were found. None of the correlations between the various CBFV indices and the indices of vehicle control and speed attained significance. In addition, the state measures taken following the short task battery did not correlate with driving performance at more than chance levels.

Table 3. Correlations of SD of lateral position with subjective state factors, across four 9-minute task periods.

| DSSQ factor | | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|---|
| Distress | *r* | .218 | .370** | .383** | .234 |
| Engagement | *r* | -.154 | -.122 | -.217 | -.139 |
| Worry | *r* | -.014 | .106 | .099 | .114 |

*Note.* * *p* < .05, ** *p* < .01

The only performance correlates found were among the post-drive DSSQ scales. Table 3 shows that distress tended to correlate positively with higher SD of lateral position; i.e., higher distress related to poorer vehicle control. Task engagement showed a non-significant trend towards a negative correlation. In addition, both distress ($r$ = -.279, $p$<.05) and task engagement ($r$ = -.242, $p$<.05) were positively associated with lower speed in the initial task period, but these relationships were not sustained into periods 2-4.

*Analyses of the DSI*

The study of driver fatigue reported in the Year 1 report (Matthews et al., 2004; see also Funke et al., 2007) investigated stable individual differences in vulnerability to driver stress and fatigue measured by the DSI (Matthews et al., 2007). Data suggested that DSI factors related both to subjective state responses to the drive, as well as to objective performance, indexed by SD of lateral position. The present study tested whether similar associations were obtained in the fatiguing driving paradigm and also tested for associations between the DSI and CBFV during driving.

The DSI scales were less effective than in the previous study (Matthews et al., 2004) as predictors of subjective state, measured with the DSSQ, post-drive. No predictors of distress and worry were obtained. Post-drive engagement was positively correlated with the DSI hazard monitoring scale ($r$ = .316, $p$<.01) and negatively correlated with DSI fatigue proneness ($r$ = .290, $p$<.05). Correlations between the DSI and performance indices did not exceed chance levels. In addition, CBFV was not robustly associated with the DSI scales. However, there was a tendency for Dislike of Driving to correlate positively with CBFV in both hemispheres, as shown in Table 4.

Table 4. Correlations of CBFV with the DSI Dislike of Driving scale, across four 9-minute task periods.

| Hemisphere | | Period 1 | Period 2 | Period 3 | Period 4 |
|---|---|---|---|---|---|
| Left | *r* | .167 | .175* | .094 | .288* |
| Right | *r* | .348** | .308* | .253 | .218 |

*Note.* * $p$ < .05, ** $p$ < .01

## Discussion

This study of simulated driving represented an attempt to discern whether the predictors of sensory and cognitive vigilance generalized to the more complex task of simulated vehicle driving. Overall, results were mixed, and further research is likely to be necessary to evaluate the utility of the approach in predicting multi-component tasks in which vigilance is only one element.

On the positive side, the simulated driving task showed several features that resembled the vigilance paradigms (e.g., Matthews et al., 2005; Reinerman et al., 2006). The profile of

stress state response was similar to that seen for the vigilance tasks, in that distress increased and task engagement declined. Effect sizes were a little smaller than those elicited by vigilance, but they were still substantial. The workload of the driving task was also fairly high, although a little lower than that of vigilance, especially in relation to mental and temporal demands. Furthermore, CBFV declined in both hemispheres and the magnitude of the effect was similar to that seen for vigilance. The present study is the first demonstration that CBFV may decline during a complex psychomotor task representing real-world skilled performance. The lateral position data suggested a temporal decrement in performance corresponding to the decrease in CBFV.

The measures taken from the short task battery corresponded well to those obtained in the previous studies of vigilance. Once again, the phasic CBFV indices were influenced by task type and hemisphere as expected on the basis of previous findings (e.g., Stroobant & Vingerhoets, 2000; Tripp & Warm, 2007). These measures also showed a similar pattern of intercorrelation as in previous studies, suggesting a partial differentiation of intra-hemispheric responses, but also some inter-hemispheric correlation. A somewhat reduced incidence of significant correlations between hemispheres may be the result of the lower sample size of this study, compared with previous ones. This study also confirmed that the right-hemisphere CBFV response was correlated with subjective task engagement; a finding obtained in the sensory but not the cognitive vigilance study. The data extend previous findings by showing that subjective task engagement and worry during the simulated drive correlated significantly with the concurrent CBFV measure taken from the left-hemisphere. It is unclear why the hemisphere correlated with subjective state should switch in relation to the two sets of state/CBFV measurements.

However, in contrast to the vigilance studies, CBFV failed to predict driver performance in relation to either the vehicle control or speed measures. Similarly, subjective state response to the short task battery was also unrelated to subsequent vehicle driving performance. However, the relevance of subjective state variation to performance was confirmed by the concurrent associations of higher distress with poorer vehicle control. Generally, driving performance was more weakly predicted by the DSSQ (and by the DSI stress vulnerability scale) than in the previous study of individual differences in simulated driving performance (Funke et al., 2007; Matthews et al., 2004).

There are several factors that may have contributed to the lack of prediction of driver performance in this study, including the relatively low sample size, which was smaller than that for both the previous vigilance and simulated driving studies. Possibly, responses to the short task battery are less diagnostic of performance of an acquired skill, such as driving, than they are of other laboratory tasks such as vigilance. In this case, response to a short driving task may be more predictive. Conversely, the simulated driving task lacked some of the features of the task used in the earlier study (Funke et al., 2007; Matthews et al., 2004) that may have added realism such as interactions with other traffic and the need to deal with stress factors (depending on the condition). The predictive validity of driving-related scales such as the DSI may depend on a greater level of interactivity with the driving environment than was provided here. It is, of course, unfortunate, that the data on vigilance during driving were lost due to mechanical failure of the simulator apparatus; possibly the independent variables would have correlated with this performance criterion.

The prediction of individual differences in driving competencies remains a pressing operational concern, given the vulnerability of stressed and fatigued military personnel to vehicle crashes. The present data provide some general support for using subjective and psychophysiological diagnostic indices in tackling this issue. The demonstration of declining CBFV during a fatiguing drive is especially encouraging. There may be other military task situations, such as controlling unmanned vehicles (UV), where monitoring CBFV will prove to be diagnostically useful. However, further work is necessary to develop the strategy for operator assessment to the point where vehicle driving may be predicted as effectively as single-task vigilance.

## Work Completed at Georgia State University

### Introduction

Broadly defined as selection for processing, attention is a superordinate category of processes that subsumes several distinct but coordinated cognitive skills. It is axiomatic that selection occurs both at input (i.e., which stimuli from the vast array of simultaneous overt and covert sensory signals get processed into behavior) and output (i.e., which of a range of competing responses get executed). However, this selectivity varies across contexts along the intensive dimension (or perhaps a better term would be exclusivity), along the spatial dimension, and along the temporal dimension. That is, there are variations in how much attention is paid, how much mental effort is expended, or how concentrated attention is. These variations however appear to be orthogonal to variability in *where* attention is allocated or scanned and in *when* attention is employed or sustained.

The multidimensionality of attention is reflected in the findings of the experimental literature, the psychometric literature, and the neurocognitive literature. It is this composite nature of the construct that has resulted in the popularity of so many different metaphors of attention–filters, resources, spotlights, and the like–across the last few decades of research on attention. Extensive research on attention has not generally served to favor one metaphor over the others, as much as it has demonstrated that each metaphor captures well some but not all characteristics of attention. Psychometric analysis of the tasks that have been used to study attention corroborate this contention. The results of factor analytic studies of attention skills, while differing somewhat in the number and nature of the specific factors, nonetheless agree that attention is comprised of multiple factors. In our own review of this literature (Putney and Washburn, 2003), we found evidence for at least three major factors of attention that have been called Focusing (concentration, mental effort), Scanning (orienting, searching), and Sustaining (alerting, vigilance).

Research on the neural correlates of attention skills has produced a similar picture, with three separable networks of attention (Posner and Peterson, 1990). The executive-attention network, involving prefrontal regions and the anterior cingulate gyrus, appears to be critical in monitoring and resolving response competition (Fan et al., 2003). The attention-alerting system is comprised of frontal and parietal areas of the right hemisphere, and are implicated in maintaining vigilance and readiness-to-respond over time. The attention-orienting network includes brain regions associated with the ability to disengage attention from a stimulus (posterior parietal lobe), to scan or shift attention (superior colliculus and surrounding areas), and to engage attention in a new location (pulvinar and other areas of the thalamus). The emerging consensus between these findings from cognitive neuroscience and those from experimental and psychometric studies is summarized in the table below.

| 1. Attention Networks | 2. Brain Regions | 3. Latent Factors | Attention Dimension |
|---|---|---|---|
| Visual Orienting Network | posterior parietal, superior colliculus | SCAN, SEARCH, SHIFT | Spatial dimension |
| Executive Attention Network | Prefrontal, anterior cingulated gyrus | FOCUS, EXECUTIVE | Intensive dimension |
| Vigilance/Alerting Network | right parietal and frontal | SUSTAIN, SORT, VIGILANCE | Temporal Dimension |
| 1. Posner & Peterson (1990): Model of the neuropsychology of attention<br>2. Posner & Fan (In press): Attention as an organ system<br>3. Washburn & Putney (1998): Assessment Software for Attention Profiles dimensions | | | |

Within each of these factors or dimensions, attentiveness can be characterized continuously, such that an individual may differ from occasion to occasion in the intensity, spatial exclusivity, and temporal durability of attention, and such that some individuals are characteristically better than others at some of these attention skills. Participants who tend to focus attention well may not sustain attention effectively, relative to other participants. Thus, the challenge for the prediction of attention on any task involves determining the type of attention that is required on the task, the attention skills of the operator who is performing the task, and the level of performance that can be expected from this participant (within the range of performance levels that he/she might produce) that that moment in time.

The goal for the research at Georgia State University was to determine whether inattentiveness in one of these factors (vigilance/alerting) can be predicted. Over the years, vigilance or sustained attention has been extensively studied (see Parasuraman, 1984, 2000; See et al., 1995). Although performance generally declines as a function of time-on-task—an effect known as the vigilance decrement (Mackworth, 1961)—this generalization provides little value for predicting the likelihood of a participant attending at any particular moment in time. For some participants, the decline in attentiveness across the vigil is precipitous; for others, performance may remain relatively stable across time (depending, of course, on the duration of the vigil and a number of parametric variables with respect to the task). For most participants, attention waxes and wanes irregularly across the vigil, such that indicators of inattention (e.g., missed target stimuli, or slow responses to detected targets) can be observed at any point during the vigil.

Having defined what performance looks like when a participant is inattentive—targets are missed, responses are slow and inaccurate—the present research focus has turned to the question “Are there other behavioral or physiological indicators that a participant is about to become inattentive?” This was the motivation for the present application-inspired research and our efforts to see whether a particular psychophysiological marker would be useful for diagnosing and ameliorating inattention—before it has an effect on performance. Changes in cerebral bloodflow velocity (CBFv) were measured using transcranial Doppler (TCD) sonography. The

studies also examined the relation between CBFv and other psychometric measures (e.g., of other attention skills or other predictive measures).

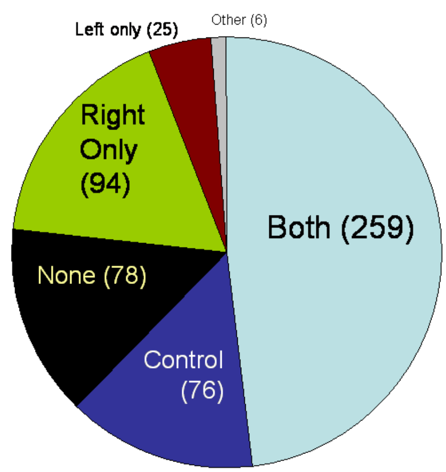
## General Method

### *Participants*

A total of 540 undergraduate volunteers were tested using TCD across studies and years at GSU. The demographic characteristics of these participants are displayed in the table below. An additional 14 participants were tested with the Watchkeeper task while wearing a head-mounted eye tracker, as described below and in the Year-2 progress report.

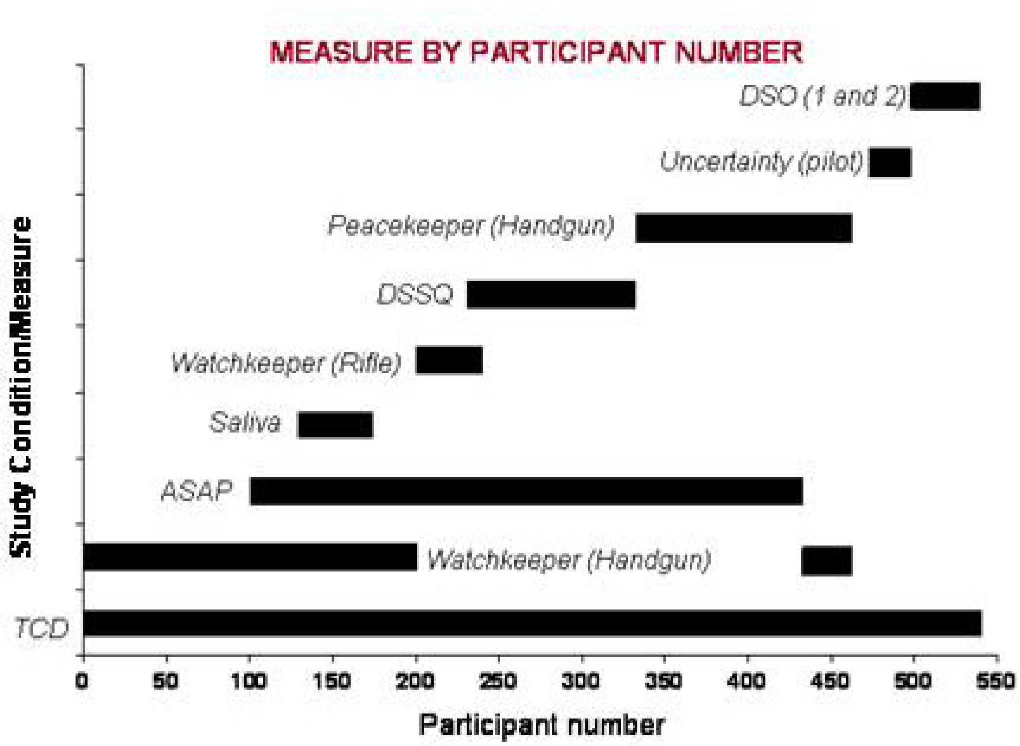
| | | |
|---|---|---|
| AGE | Mean = 19.65 years | 83% < 22 years |
| GENDER | Female= 399 (74%) | Male = 141 (26%) |
| Race/Ethnicity | Black/African-American = 194 (36%) | |
| | White/Caucasian = 189 (35%) | |
| | Asian = 71 (14%) | |
| | Hispanic = 33 (6%) | |
| | Other = 53 (9%) | |

The proportion for which a reliable CBFv signal could be obtained for both hemispheres versus for one hemisphere versus for neither hemisphere is displayed in the figure. Of the 279 participants for whom we could not obtain reliable bilateral TCD signals, 76 were treated as controls. These participants completed the task procedures wearing the TCD apparatus, but no CBFv data were collected. The TCD apparatus was removed from participants in the "none" group when it was clear that we could not obtain a reliable TCD signal from either cerebral hemisphere.




Across the studies, 3 participants at GSU experienced adverse effects from testing. These participants reported headaches or nausea associated with the TCD apparatus or testing. These participants were immediately dismissed from the study and the adverse effects were reported to the GSU Institutional Review Board.  No follow-up treatment was requested or required. It is impossible to determine from this small number of incidents whether the symptoms were directly related to the TCD apparatus or study conditions; in each case however, the participant's report was that the TCD headband created the physical distress, and the participants reported alleviation of the symptoms once the apparatus was removed.

Each undergraduate participant was tested on several behavioral tasks and with different psychophysiological measures, depending on the experiment into which they were recruited. The figure below illustrates distribution of subjects to tasks or measures across these studies.




For the present analyses, results are reported for those participants for whom reliable bilateral TCD signals were obtained, and for whom the relevant tasks were completed (total N = 444). Accordingly, the table below summarizes sample sizes for each of the present analyses:

| Study/Task | N |
|---|---|
| Study 2, Aim 1, analyses a, b : Investigate the relation between TCD and Army-relevant criterion-task performance | 79 |
| Study 2, Aim 2, analysis a: Test whether psychophysiological assessments (including TCD) predict future Army-relevant task performance | 83 |
| Study 2, Aim 2, analysis b: Trait differences in CBFv predict Watchkeeper task performance | 40 |
| Study 2, Aim 2, analysis c: Pupil dilation and TCD in Watchkeeper performance | 31 |
| Study 2, Aim 2, analysis d: Relation between salivary cortisol task performance, and TCD | 33 |
| Study 5, Aim 1, analysis a: Relation of TCD and Peacekeeper-task performance | 50 |
| Study 5, Aim 1, analysis b: Relation of TCD and Defensive Strategic Operations-2 performance | 20 |
| Study 6, Aim 1, analysis a: ASAP and Watchkeeper performance | 43 |
| Study 6, Aim 1, analysis b: ASAP and TCD | 30 |
| Addendum (Pilot study): Does TCD predict decision uncertainty? | 13 |
| Addendum (thesis study): Does TCD reflect the capacity of visual working memory? | 22 |

Note: “Study” and “Aim” refer to study numbers within original project proposal.

***Tasks and Measures***

Watchkeeper. The Watchkeeper task was inspired by the demands faced by a sentry or other individual who must maintain vigilance on a field of view, detect the presence of persons who may or may not be threats, and shoot accurately when threats are presented. The Watchkeeper task was modeled loosely after the marksmanship range at the Aberdeen Proving Grounds. A grassy field, complete with trees and hills, was projected as the stimulus background in front of participants (see figure). The display was projected on a screen, and occupied approximately 45 degrees of visual angle (approximately 2.3 meters diagonal). The participant was generally seated approximately 2 meters from the display and was instructed to monitor this scene for 27 minutes, searching for threat images (orange rectangles) that appeared infrequently from behind the trees or over the hills and then disappeared again behind the blinds. Nonthreat images (blue rectangles) appeared more frequently, but with comparable stimulus locations and display durations. The targets were scaled so that those that distance and size covaried as they would in a natural scene. Participants saw threat or nonthreat stimuli with an event rate averaging 10/minute. The ratio of nonthreat:threat stimuli was 80%:20%.

To respond to these images, participants used one of three manipulanda (assigned as a between-subjects manipulation). Some participants used the computer mouse to click on the threat

images when they appear. Other participants responded with a replica of a 9-mm handgun, modified by LaserShot, Inc. to produce a laser blip on the screen when fired. This laser spot is interpreted by our software as a mouse click, such that the time and location of each shot is recorded. The third available response manipulandum was a LaserShot-modified rifle. The rifle was similarly modified so as to simulate a mouse click on the screen. The task and response apparatus, including the head-mounted TCD sensors, are illustrated in the figure. No response was required to the nonthreat images.

Several measures of attention (or, alternatively, of inattentiveness) are available from the Watchkeeper task. The first measure is reflected in the signal-detection decisions whether or not to shoot at a particular stimulus. Hit rate (the proportion of times a target appeared on the screen and a response was made) or its converse (miss rate, or the proportion of times a target appeared without a shot being produced) are primary indicators of attention. False-alarm rate (shots fired following the presentation of nontarget images) supply information about the bias and sensitivity of participants making the shoot/don't-shoot decisions.

The latency to respond to a target stimulus is a second measure of attention in the Watchkeeper task. Shots fired during target-stimulus presentations are timed, with the underlying assumption that faster responses reflect more intense attentiveness to the task.

Marksmanship accuracy was measured by the distance between the target-center and the location of a shot on the screen.

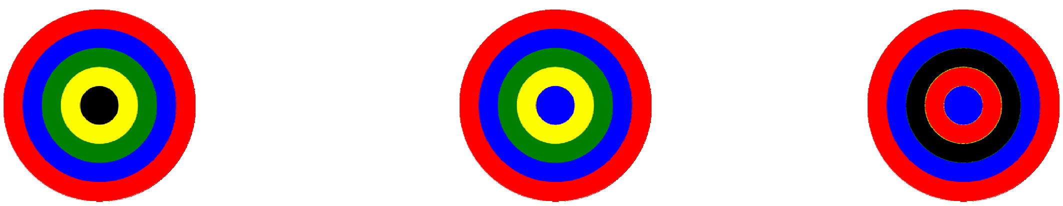
Thus, we operationalized inattention as an increased probability of missing target presentations on the Watchkeeper task, as longer response latencies when responses are made to target images, and as decreased marksmanship accuracy as a function of time-on-task.

Marksmanship calibration. Generally speaking, of course, individuals differ in marksmanship accuracy, and accuracy would be expected to improve with practice (as we found in Year-1 of this project). To calibrate marksmanship accuracy and to provide initial practice for all participants, thereby minimizing the amount of improvement in accuracy we obtained during an experimental session, each participant completed a preliminary task requiring a series of nine targets appearing all around the screen to be shot. Each target was a red circle approximately 10 cm in diameter, projected on the wall. Sound and visual feedback indicated whether the shots were accurate. These responses were not speeded or timed, and the series could be repeated until acceptable levels of marksmanship accuracy were obtained (i.e., until the participant could reliably hit the targets).

Data were not recorded for marksmanship calibration; however the experimental session was not continued until both the participant and the experimenter were satisfied that the weapon could be shot accurately. Most participants required only a single series of nine targets before they were ready to proceed with criterion-task testing.

Peacekeeper task. A continuous decision-making task was developed for this study. The participants were presented with an alley scene (see figure) which afforded numerous potential locations where threat or nonthreat images could appear.

For this research, bulls-eye images were use to depict threat and nonthreat stimuli. These images allowed the manipulation of a difficulty variable where the nontarget images could vary systematically in similarity to the threat image, potentially creating varying degrees of difficulty (and uncertainty) in distinguishing threat from nonthreat images—unlike the Watchkeeper task, where the two classes of stimuli were always clearly distinguishable. The stimuli below illustrate this manipulation where the stimulus on the left is the threat (shoot) image and the two stimuli on the right are nontargets that are progressively less similar to the target.



For the present study, stimuli appeared in locations like windows, doorways, side alleys, and from behind other sources of natural cover to simulate the demands of a series of speeded shoot/don't-shoot peacekeeper decisions in a naturalistic setting. Stimuli were scaled with respect to size so as to reflect the relative distance of some targets relative to others. Stimuli remained on screen for 1000 to 2000 msec, randomly determined. Inter-stimulus intervals ranged randomly from 2 to 5 seconds, and the ratio of threat to nonthreat stimuli was 1:1.

The Peacekeeper task yielded measures of decision accuracy, marksmanship accuracy, and decision latency. Several types of errors were scored (but no real-time feedback was provided, other than any discrepancies between the target location and the visible blip from the shot): erroneous decisions (shooting a nonthreat image), poor response latency (failure to shoot a threat image within the presentation period), or marksmanship errors.

All participants tested with the Peacekeeper task completed 400 trials (i.e., 400 stimuli were presented, and 400 shoot/don't-shoot decisions were recorded). This task was also used with a training manipulation. The effects of various amounts of training or practice upon these performance measures were analyzed in one study.

DSO-2 task. The defensive systems operation (DSO) task was designed to permit measurement of participants' learning and problem-solving skills. It required participants to select from four

available defensive systems to various threat conditions. Feedback was provided to indicate whether the defensive system was at least equal to the level of threat. Thus, across trials and problems, students learned to respond to threats with the appropriate defensive system.

The four defensive systems and the four threat levels were symbolically coded so it was impossible to determine just by name the severity of each treat, or the potency of each defensive option. Each defensive system had a cost associated with it, so participants could not simply use the most extreme response on every trial. This, participants had to guess initially, but increasingly to respond with the appropriate defensive system on the basis of knowledge gleaned from trial-and-error feedback.

The task used a text-based format. Each trial began with a display of the particular threat (or threat level) for that trial (coded PONGO, ZEPHER, BANTO, and WORPA from least to most threatening, although there was no way for participants to know this order without experience). The participant also saw a display of the possible defensive systems (coded 1, 2, 3, and 4) and the number of times each system could be used for all the remaining trials. The participant was prompted select an option from one of the available defensive systems. After this response, the participant was informed as to whether the defensive system was effective or ineffective. Effective responses earned points for the participant, whereas ineffective defensive systems cost the participant points. The participants were instructed to earn as many points as possible in 20 trials. Each volunteer completed 5 blocks ("games") of 20 trials.


The DSO task described above was the second version we developed and tested. An earlier version (DSO-1) was also used with a subset of participants. In the DSO-1 version, two units of information were presented (one on the left side of the screen and the other to the right of midscreen) to participants on each of a series of trials. The each unit of information was a stream of ones and zeros (e.g., 0110100), where each digit coded some binary threat condition (e.g., enemy troops in sector one, two, three, and so forth). The participant had to determine whether the information unit on the left side of the screen or the information on the right side of the screen represented the greater risk, and consequently in which direction to allocate resources. On each trial, the configuration of ones and zeroes changed randomly, but the rule for determining which stimulus to select (e.g., select the unit in which enemies are located in the outermost two sectors, irrespective of the values of the intervening digits) remained the same for each problem. Participants received feedback after each trial to indicate whether their response was correct or incorrect, and consequently could learn the underlying rule and thereby optimize their defenses toward the more threatening stimulus. A problem ended when the participant reached a performance-based criterion (67% accuracy or 80% accuracy) and a new problem was initiated with a different rule (e.g., select the unit in which at least four sectors are marked with "1").

Each participant was assigned 10 problems like this. However, few participants reached criterial performance levels for all 10 problems. The task was too difficult for most of the 32 participants tested, despite our attempts to modify the task to make it easier without losing the continuous problem-solving and learning attributes. Finally, we abandoned this paradigm for the much better DSO-2 version described above.

ASAP tasks. The Assessment Software for Attention Profiles (ASAP) was developed at GSU with support from the Air Force Office of Scientific Research. The ASAP is a self-paced, computer-based battery designed for identifying individual differences in skill or ability across different factors of attention, and for studying the relation between profiles of attention skills and criterion-task performance. The ASAP battery consists of a series of computerized versions of many of the standard testing paradigms from cognitive psychology and neuropsychological assessment. The full battery taps the three major latent factors of attention that have appeared in the literature: attention focusing (also called executive attention or concentration), attention scanning (also called orienting or searching), and attention sustaining (also called alerting or vigilance).

In the present study, participants were tested with a subset of tasks selected from the ASAP battery (Washburn & Putney, 1998). Tasks were selected from this battery to provide multiple measures of performance on each attention factor (as indicated by prior factor analyses) within the time permitted in an experimental session. Response latency and accuracy were recorded for each task.

The simple and choice speeded-response tasks (RT-1 and RT-2, respectively) were two-choice response-time tasks requiring the participants to left-click the mouse when an F appeared on the screen and to right-click the mouse when an E appeared on the screen. Letters appeared sequentially in the middle of the screen, with a 2.5-s average interstimulus interval. RT-1 included ten trials (probability of an F = 1.0), and RT-2 included 20 trials (probability of an F = 0.5).

In the CUE and ANTI tasks, participants continued to determine the identity of a target letter (E or F), but the letters appeared randomly on either the left or right side of the screen. Each task included 24 trials. On some trials, the participant was cued to the location of the target just before the letter appeared. In the CUE task, these cues appeared either centrally (i.e., an arrow flashed at the midscreen fixation point to indicate where the target letter would appear) or peripherally (in the location at the edge of the screen where the target letter would appear). Responding could be facilitated (i.e., could be faster and more accurate) following central cues if the participant made an endogenous or intentional shift of attention to the target location. Peripheral cues produced an exogenous or elicited shift of attention that could facilitate performance. The benefits of central and peripheral cuing were measured against baseline trials in which no cues were given.

The INHIB task was a speeded stop-signal task in which the participant monitored streams of letter pairs, clicking for each pair that did *not* contain at least one F. If an F appeared in either

letter of the pair, however, the participant was to refrain from responding. Stimuli appeared with a 50 msec. stimulus offset asynchrony after a response, and after a 2000 msec. delay following a nonresponse to an F stimulus. The probability of an F appearing in the pair was 0.25, so that we could examine the likelihood of a false-alarm error as a function of the number of consecutive “go” responses. Each participant completed 40 trials.

SEARCH1 was a task requiring participants to search quickly and accurately for a target letter in an array of simultaneously presented letters. There were 30 trials, with stimuli presented every 5 seconds. The target letter was F, and the array contained 10, 40, or 70 Es, Ls, and Ts. Participants were required to press the left mouse key if there was an F presenting the array, and the right mouse key if there was no F present. More importantly, reaction times also generally vary as a function of number of letters in the array. Participants who perform well on this task were those who scanned quickly and accurately through the arrays of 10, 40 or 70 letters.

Extending the RT-2 task to a six-minute vigil, with nontarget (E) stimuli four times as likely as the target letter (F), makes the task a continuous performance task (CPT). Each participant completed the six-minute, 360- trial CPT. Stimuli appeared every 1.5 seconds. Ideal performance required consistent and rapid responses to each target letter, but no response to the nontarget stimuli.

The STROOP task required participants to respond to the colors of various words. The words were the names of colors (blue, red, yellow, or green) or simply “XXXXX” on baseline trials. However, the word itself was irrelevant; the participants were required only to respond to the color in which the word was printed. This presentation color could be congruous or incongruous with word meaning. For example: the word ‘blue’ might have been written in yellow letters, the word ‘red’ might have been printed in blue letters, and so forth. The participant’s task was to name the color of the letters rather than to read the word (e.g., to respond “yellow” and “blue” in the example above by pressing the left mouse button; red or green stimuli should have produced a right-click of the mouse ). Participants were required to complete 50 trials, with stimuli appearing every 5 seconds. Because the participant’s habitual response is to read the word, responses are generally less accurate and slower when they view an incongruous trial than when they view a congruous (the color of the word and the meaning of the word are the same) or a baseline (the text is X’s written in a certain color) trial.

Recently, Posner and his colleagues developed a single task that they argue provides measures for three different factors or networks of attention: the Attention Network Task (ANT; Fan, McCandliss, Flombaum, Thomas, & Posner, 2003; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Rueda, et al., 2004). This task required participants to determine which direction (left or right) a central arrow presented on a screen pointed. The central arrow may have been flanked by other congruent arrows (e.g., ← ← ← ← ←), incongruent arrows (e.g., → → ← → →), or neutral stimuli (e.g., --- --- ← --- ---). In this task, participants were sometimes cued as to when but not where the center arrow would appear. On other trials, the participants saw cues that indicated both when and where the string of arrows would appear. Reaction times typically vary based on the congruency of the flanker arrows and the type of cue. In general, participants are

faster in responding when they are shown congruent flanker arrows rather than incongruent flanker arrows; when the cue is spatial (i.e., appears in the location where the target arrow will appear), rather than central (i.e., appears in the center of the screen); and when they are cued as to when the target arrows would appear compared to when no cue was provided at all. A total of 96 trials were presented to participants, at a rate of one trial every five seconds.

These tasks represent a subset of the ASAP tasks used in the past. The present tasks were selected to accommodate session-duration limits and to provide representative and strongly-loading tasks for each of four latent factors of attention. In previous factor-analytic studies in which the full ASAP battery was used, the response-time measures from these tasks have been shown typically to load on the following four latent variables: STROOP and RT-2 load together on an attention-focusing (or mental effort) factor. SEARCH reflects attention scanning, whereas CPT loads on the sustained attention factor. The ANT task produces three orthogonal, derived measures: an executive attention or focused attention measure (incongruous trials minus congruous trials) similar to STROOP and RT-2. An ANT "alerting" measure (central cue minus no cue response times) reflects the same sustained-attention factor as CPT. The "orienting" measure available from ANT (spatial cues minus double cues) provides a second measure of attention scanning, complementing SEARCH-task response times.

<u>DSSQ</u>. A computerized version of the Dundee Stress State Questionnaire was administered to some participants. This measure is described in the UC portion of this final report.

<u>Uncertainty pilot</u>. Participant's performance in the threat-detection tasks, particularly the Peacekeeper task, inspired a pilot study that was not described in the funded proposal. The question that motivated this study is, "Can TCD (or other measures) indicate when a participant is uncertain in a decision-making situation?" That is, are there psychophysiological or behavioral indicators that participants are unsure whether to shoot or not, whether a stimulus is a friend or foe, whether to deploy a defensive system or not? This question could not be analyzed with the tasks described above and in the original proposal. However, a psychophysical paradigm that has been used in other research at the GSU laboratory and elsewhere affords one possibility for investigating this question. This task and the results of the pilot study will be reported in the addendum to this final report.

<u>Psychophysiological measures</u>. In addition to TCD measures, described elsewhere in this final report, several psychophysiological measures were collected at GSU from subsets of the sample of participants. Fourteen participants' pupil dilations and eye movements were monitored and recorded using an ISCAN RK-426PC eye-tracker/pupillometer as the participants completed the Watchkeeper task (using a mouse rather than firearm to respond to the stimuli displayed on a computer screen). Other participants (N = 45) provided saliva samples before and after testing. These biosamples were analyzed for cortisol and testosterone changes that might relate to task performance or CBFv.

***Additional tasks***

VSTM task. An additional task that was not described in the original proposal tested whether TCD could be used to indicate the capacity of working memory for visuospatial (nonverbal) information. This task was administered as part of one of the GSU investigators' MA research, and thus is described in one of the "reportable outcomes" included in this report. However, the 42 participants tested on this task were not included in the total of 540 undergraduate volunteers discussed above.

RNJ task. Another "bonus" task (in the sense that it was not part of the original proposal, but could be administered to provide additional data on a question broadly related to the funded project) was a relative numerousness judgment task. A GSU graduate student used a different transcranial technology—transcranial magnetic stimulation (TMS)—in his doctoral research to examine the cerebral lateralization and localization of cognitive processes associated with estimating numerousness (e.g., how many stimuli are presented). We seized the opportunity to relate findings from TCD to those from TMS and neuroimaging studies by testing 33 undergraduate volunteers on a RNJ task. These 33 participants were not counted among the 540 discussed above, but the results of this study are included among the "reportable outcomes" in this final report.

The RNJ task involved rapid presentations of numerical stimuli (Arabic numerals or arrays of dots) to the left or right visual hemifields. Presentations of 150 msec that were subsequently masked by a checkerboard pattern ensured that the visual information was first processed by the visual cortex of one, but not both, cerebral hemisphere. Participants were then required to judge the relative numerousness of the array, either by matching the numeral to its quantity (or vice versa) or by indicating which stimulus was more numerous. Each participant completed 120 trials of this task.

### *General Procedure*

For each of the studies reported here, participants were recruited through the undergraduate participant pool at GSU and volunteered in partial fulfillment of course requirements. Participants were individually tested within 2-hr experimental sessions. An experimenter remained present with each participant for the duration of the test to verify the participants' comfort and the continuous functioning of all equipment and software. After reading and signing the consent form and, optionally, completing a demographics questionnaire, each volunteer received instructions for the study.

After verifying that the participant had no questions, the experimenter proceeded to fit the TCD headband and transducers onto the participant and to search for an appropriate and consistent ultrasound signal. A consistent signal was determined by the wave form of the signal. If the wave form was the same from heartbeat to heartbeat, then it was stable and consistent. The participant had to be able to turn their head from side to side slowly and not have had the signal disappear or become unstable. In some cases, the majority of the 2-hr test session was used to acquire a reliable and stable ultrasound signal. A small amount of Aquasonic-100 ultrasound transmission gel was applied to the face of each transducer and to the skin at the transtemporal

windows to enhance the transducer's signal reception. Hemovelocity was measured in the middle cerebral artery (MCA) in both hemispheres. The MCA was recorded at depths of 48 mm to 56 mm, which was measured as the distance between transducer face and sample volume. The recording depth was adjusted by 2-mm increments to compensate for differences in the skull size of the participant. If after extensive effort it was determined that a TCD signal could not be obtained from the MCA in both hemispheres, the participant was permitted to continue in the experiment by completing the behavioral tasks. CBFv was recorded in one hemisphere even if the other hemisphere signal was not acquired. However, only participants that presented a consistent CBFv signal from both hemispheres have been included in data analyses completed to date.

After securing the reliable and stable signal and ensuring that the TCD headband was comfortable for the participant, the experimenter instructed the participant to stare at the blank computer screen for two minutes. During this period, baseline CBFv was recorded. The participants were instructed to relax comfortably and to remain still and silent during the baseline recording. (To avoid possible contamination of the TCD data, the participants were discouraged from talking throughout the experiment—unless to report discomfort or to request a break. Vocal responses were not required for any task.)

After the baseline period, stress measures were taken (if scheduled for that particular participant). That is, each volunteer who was scheduled to provide salivary samples for that study was asked to spit into a vial at this time. Participants who were scheduled to complete the DSSQ were administered the pre-test version of the questionnaire at this time.

The volunteers were next tested on the Army-relevant criterion task for their study (i.e., Watchkeeper task, Peacekeeper task, DSO task). For the shoot/don't-shoot tasks, participants first completed the Marksmanship Calibration task to familiarize themselves with the firearm and to calibrate the LaserShot recording system. Subsequently, they were tested on the 28-minute Watchkeeper task or the 400-trial Peacekeeper task, described above. Participants completing either version of the DSO task faced the computer screen during testing and responded using the computer keyboard.

Students who volunteered for the Uncertainty Pilot Study or the VSTM memory study completed their primary tasks at this point in the test session. In addition, participants who were scheduled to provide data regarding stress completed the post-task DSSQ or provided a post-task saliva sample at this time.

Volunteers who were participating in a study that included ASAP testing were allowed to complete those computerized tasks at this point. Still wearing the TCD apparatus, the participants faced the computer screen and completed the ASAP tasks using the mouse as a response manipulandum.

Finally, the TCD apparatus was removed from the participant, the experimenter explained the study and answered any questions, and the participant was dismissed.

## Results

Results from the studies analyzed for this report are structured in relation to the series of specific aims and hypotheses listed in the Table on p. 40. These analyses support the overarching aims of testing the relationship between TCD and a variety of tasks of military relevance, and comparing the diagnostic validity of TCD and other psychophysiological indices.

***Study 2, Aim 1 : Investigate the relation between TCD and Army-relevant criterion-task performance***

Participants monitored a field display and attempted to remain vigilant in order to make fast and accurate shoot/don't-shoot decisions—and when a threat stimulus was detected, shots that were accurate with respect to marksmanship. Stimuli appeared from behind trees or other blinds, with infrequent ($p = .20$) threat images. Orange and blue rectangles were used as stimuli to make the basic discrimination easy for all participants, such that any changes in performance across time could be attributed to variations in task-directed attention.

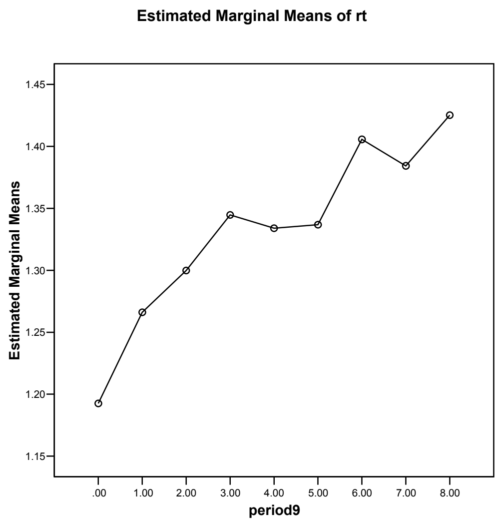
Hypothesis 2.1.1: Changes in task performance across the vigil will correlate with changes in cerebral bloodflow velocity, particularly in the right cerebral hemisphere.
Hypothesis 2.1.2: Changes in CBFv will differ between trials in which a target is detected, shot quickly, shot accurately and trials in which the target is missed, or detected but shot slowly or with poor marksmanship.

a. Relation between Watchkeeper signal-detection performance and TCD. False-alarms were very rare for the Watchkeeper task (89% of participants had 0 false alarms, 5% produced a single false alarm, and 1 participant produced 6 false alarms). Consequently, signal-detection analyses were focused on hit-rate rather than a transformation to d' or another measure. Overall hit-rate was 0.87 (std = .17), and did not vary significantly as a function of watchperiod (see table).

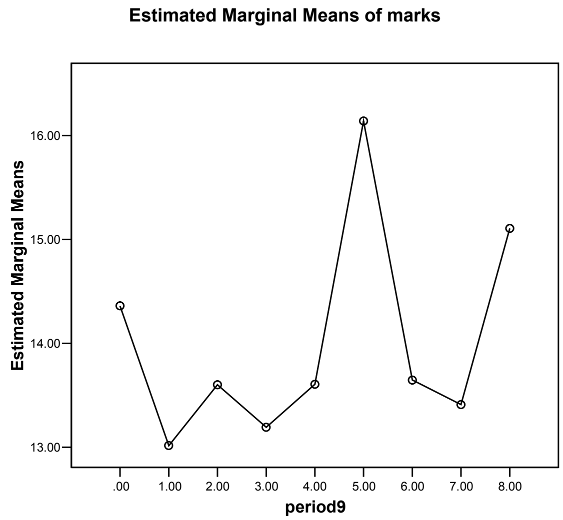
Left- and right-hemisphere CBFv values were computed for each participant during signal detection hits (firing the weapon when the threat stimulus was displayed) and misses (failure to response during presentation of the threat stimulus). Analysis of variance was used to compare the speed of bloodflow velocity in the two hemispheres for hits and misses. No significant differences were found, and there was no significant interaction between the variables (all $p > .10$). That is, Hypothesis 2.1.2 was not supported: bloodflow velocity (either in absolute terms or relative to baseline) was not different for signal-detections hits and misses.

b. Relation between real-time Watchkeeper performance and concurrent TCD. For descriptive analysis, each participant's Watchkeeper vigil was initially divided into nine equal time bins. Mean shot latency on trials in which a target stimulus was presented (i.e., correct "shoot" decisions) increased across the watchperiods. This effect is displayed graphically in the leftmost figure in the panel below (showing mean response time on the y-axis and watchperiod on the x-axis). In the right panel, a similar graph for changes in marksmanship error (where higher

numbers = more error, and every 10 corresponds to an increase in shot error of approximately 3 cm in the horizontal and vertical direction). Here, the overall trend in marksmanship error across the vigil is less obvious.

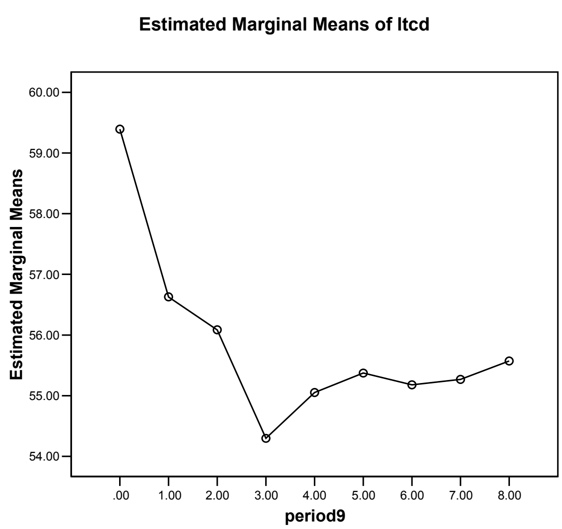



Watchperiod (3-min intervals)
Standard deviation range 0.30 to 0.33

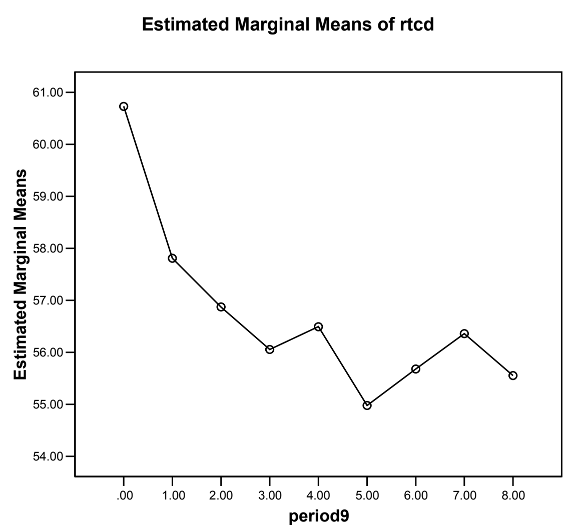



Watchperiod (3-min intervals)
Standard Deviation range 13.8 to 20.0

The figures below show comparable functions for mean CBFv relative to baseline (y-axis) across vigilance periods (x-axis), in the left (left graph) and right (right graph) hemispheres.




Watchperiod (3-min intervals)
Standard deviation range 11.6 to 14.1




Watchperiod (3-min intervals)
Standard deviation range 11.9 to 13.1

For inferential analyses, data were re-binned into four equal bins per participant so as to minimize the number of watchperiods with missing data (e.g., because no response was

produced). The table below summarizes the results from the 79 participants with valid bilateral TCD CBFv data.

| Measure | Period 1 mean (std) | Period 2 mean (std) | Period 3 mean (std) | Period 4 mean (std) | ANOVA |
|---|---|---|---|---|---|
| Hit rate | 0.90 (0.14) | 0.89 (0.19) | 0.89 (0.17) | 0.86 (0.21) | $p > .10$ |
| Response latency | 1.224 s (.256) a | 1.327 s (.296) ab | 1.364 s (.283) b | 1.395 s (.280) | $F(3,234) = 30.5, p < .001$ |
| Marksmanship error | 13.5 (7.08) | 13.8 (7.18) | 14.2 (7.9) | 14.3 (8.0) | $p > .10$ |
| Left CBFv | 58.2 (13.3) a | 55.5 (12.4) a | 55.6 (11.5) b | 54.5 (11.4) b | $F(3,234) = 13.4, p < .001$ |
| Right CBFv | 59.6 (11.5) a | 57.2 (11.0) ab | 56.4 (11.0) b | 56.0 (10.1) | $F(3,234) = 23.0, p < .001$ |

(Lower-case letters indicate significant differences between adjacent cells for each measure, from post hoc comparisons.)

Changes in left-hemisphere CBFv and right-hemisphere correlated negatively and significantly but modestly with response time ($r$ = -0.13 and -0.10, respectively). Only the right-hemisphere CBFv measure correlated positively and significantly with marksmanship error, although again the relation was small ($r$ = 0.07). Hypothesis 2.1.1 was supported by these findings, as the correlations were significant, but not substantial.

***Study 2, Aim 2 : Test whether psychophysiological assessments (including TCD) predict future Army-relevant task performance***

Having established small but reliably related changes in performance and CBFv, Watchkeeper-task data were analyzed to determine whether changes in bloodflow velocity precede and predict variations in attention. In this study, we also compared TCD as a predictor of variations in attention to other potential indicators of task-related inattention.

Hypothesis 2.2.1: Changes in cerebral bloodflow will be diagnostic of task-reflected inattention well in advance of the presentation of the target stimulus.

Hypothesis 2.2.2: Participants who perform best at the Watchkeeper task (fastest and most accurate shots) will show a different pattern of CBF changes than will the participants who score in the bottom quartile of Watchkeeper task performance.

Hypothesis 2.2.3: CBFv measures from TCD will provide predictive value above that available from another psychophysiological measures (pupil dilation, salivary cortisol).

<u>a. Relation between TCD and future Watchkeeper performance</u>. The data described above (Study 2, Aim 1) reflect CBFv data from the 2-sec interval before a target was presented. Extending backward in time before presentation of a target stimulus, we examined whether Watchkeeper performance could be predicted by variations the TCD measure. These analyses

required computation of mean cerebral bloodflow velocities 2-s before presentation of a target stimulus, 4-s before target presentation, 6-s before and so forth. Each task performance measure was then regressed against these predictor measures, and also against response latency on the last trial in which a response was made, watchperiod (time on task, interval coded into four bins), the number of stimuli (targets and nontargets) since the last response, the interaction of watchperiod and time-since-last-response. Regression was used for these exploratory analyses, entering participant ID into the regression first to capture within-participant variability in performance, and using every valid target event for each of 83 participants.

For Watchkeeper shot latency (response time), about 14% of the variance is explained by a model that adds the latency of the previous shot, the amount of time the participant has been participating in the task, and the left-hemisphere CBFv measure. One can use the CBFv measure from 18 seconds before a target presentation without losing predictive value from the TCD data. Note however that little of the variance accounted for by this statistically significant regression model is uniquely associated with the CBFv measure. Thus, Hypothesis 2.2.1 received partial support: The regression model favored CBFv measures well in advance of the target presentation; however the proportions of variance accounted for by these analyses were only modestly improved by the TCD measures.

**Model Summary**

| | | | | | Change Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | R Square Change | F Change | df1 | df2 | Sig. F Change |
| 1 | .071[a] | .005 | .005 | .3099 | .005 | 33.621 | 1 | 6642 | .000 |
| 2 | .312[b] | .098 | .097 | .2951 | .093 | 681.226 | 1 | 6641 | .000 |
| 3 | .349[c] | .122 | .121 | .2912 | .024 | 180.984 | 1 | 6640 | .000 |
| 4 | .369[d] | .136 | .136 | .2888 | .015 | 112.381 | 1 | 6639 | .000 |
| 5 | .371[e] | .138 | .137 | .2886 | .001 | 10.912 | 1 | 6638 | .001 |

a. Predictors: (Constant), SUB

b. Predictors: (Constant), SUB, PRT

c. Predictors: (Constant), SUB, PRT, PERIOD

d. Predictors: (Constant), SUB, PRT, PERIOD, L9

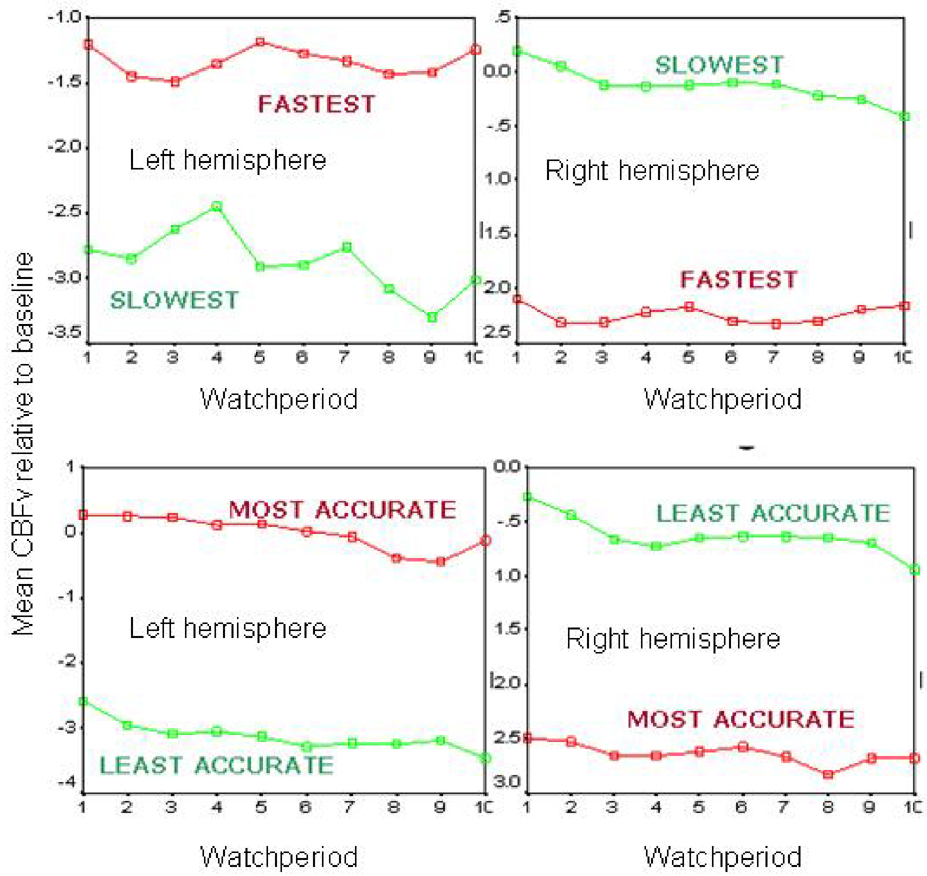
e. Predictors: (Constant), SUB, PRT, PERIOD, L9, L1

Key to regression terms: SUB = subject ID (random factor used to capture within-subject variability); PRT = response time on the previous correct shot; PERIOD = watchperiod; L9 = left hemisphere CBFv from 18 seconds (9 stimuli X 2 s per stimulus) before the target presentation; L1 – left hemisphere CBFv from the 2 seconds immediately preceding target presentation.

The prediction of marksmanship error was not improved by including CBFv measures from earlier in the vigil. The best model, which primarily includes the CBFv through the right hemisphere in the two seconds preceding the target, accounted for less than 2% of the marksmanship variance.

<u>b. Trait differences in CBFv predict Watchkeeper task performance</u>? One curious finding from the Watchkeeper study is evident when one uses quartile splits to group participants according to task performance. That is, one can separate those participants who shot target stimuli most rapidly compared to those who shot target images most slowly. Similarly, we used quartiles to identify those participants who had the best marksmanship to compare with those participants who had the most error in marksmanship.

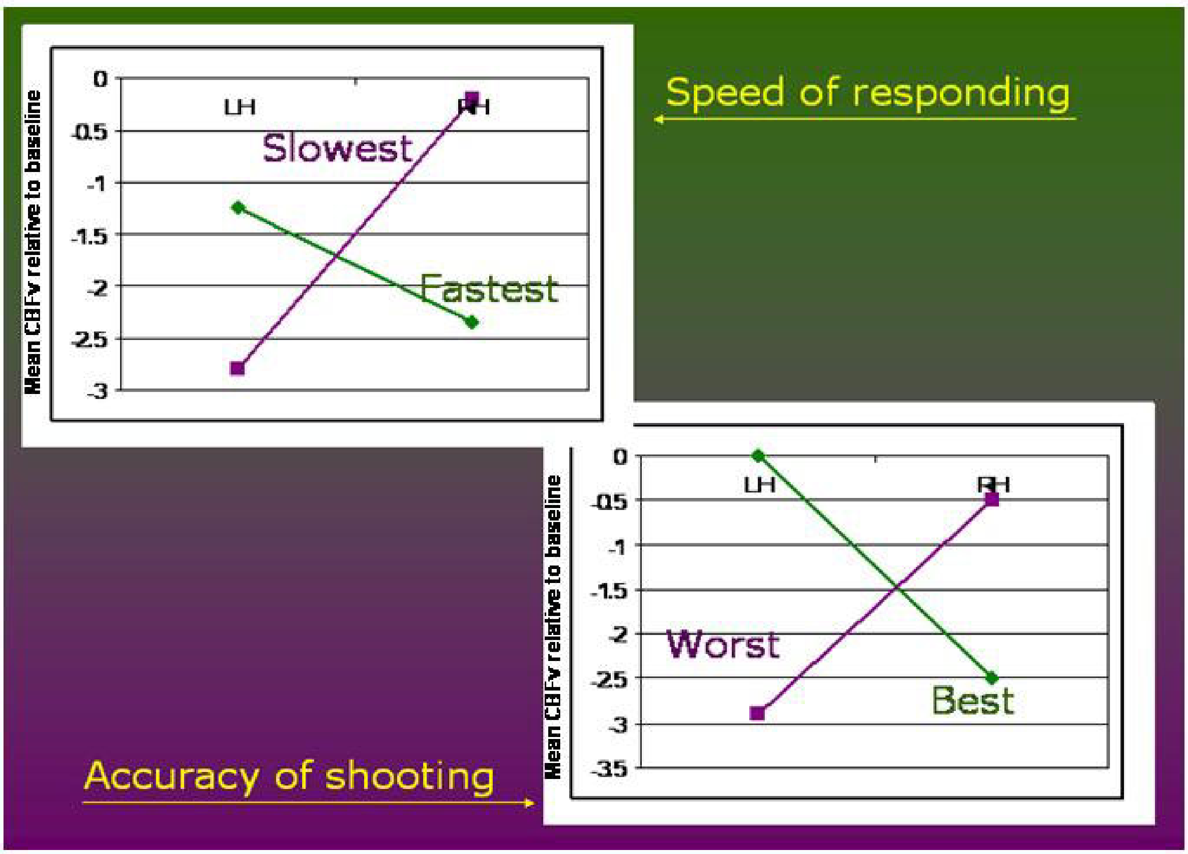
Large and statistically reliable differences were observed between these groups in the speed of CBF relative to baseline. Interestingly, these differences were stable across the vigil; that is, they were just as pronounced during the first few trials of the Watchkeeper task than in the last few.




(3-min intervals) (3-min intervals)

This effect remains apparent when the scale of the y-axes is standardized and means are collapsed across the watchperiods. Here it is clear that participants who performed best on the task (fast, accurate shots) show significantly faster CBF relative to baseline in the left hemisphere than in the right hemisphere, whereas those participants who performed worst on the

task (slow shots with poor marksmanship) were characterized by significantly faster (and more baseline-like) CBFv in the right hemisphere than the left hemisphere. Note that the quartile-based groups for shot speed and marksmanship accuracy are independent of one another. The people in the "fast shot" group are not necessarily the same as the people in the "accurate shot" group. Nevertheless, the predictive relation between CBFv in the two hemispheres and performance is consistent across these two analyses. (All pairwise comparisons are significantly different in each figure, $p < .05$). Hypothesis 2.2.2 was supported by these findings, although the direction and degree of the effect were counterintuitive.




(Note : x-axis labels on 0-line)

One possible interpretation of these results is that a measure like lateralized activity differential (the difference of CBFv in the left and right hemispheres, each relative to baseline) may provide a useful selection measure for predicting subsequent shoot/don't-shoot task performance. What is counterintuitive about this result, however, is that CBFv was slower than baseline in all conditions. That is, the baseline period (when participants were sitting silently staring at a blank screen) is associated with faster blood-flow velocities than is performance of the Watchkeeper task (even early in the vigil), and even slower CBFv in the right hemisphere is associated with

best performance on the Watchkeeper task; however, even slower CBFv in the left hemisphere is associated with poorest Watchkeeper performance.

It should be noted that we saw better performance that was associated with slower CBFv relative to baseline in other tasks as well (e.g., Peacekeeper, VSTM). This makes little sense if TCD provides a measure of brain activity. It is reasonable if TCD provides a measure of arousal, if one assumes that participants are over-aroused and anxious during the baseline period. This counterintuitive result merits further investigation.

c. Pupil-dilation versus TCD in Watchkeeper performance. This result was described in the Year-2 annual report. One study described in the original proposal compares TCD with occulomotor and pupillometric indicators of inattention. Unfortunately, pilot studies revealed the impossibility of using the head-mounted TCD apparatus on participants simultaneously with the head-mounted ISCAN eye-tracker/pupillometer that we have available at GSU. The two apparatus could not be positioned simultaneously on a participant so as to allow stable detection of cerebral bloodflow (i.e., the signals could not be found and, frequently, the transducers could not be locked securely into position), and the eye-tracker moved spuriously causing calibration errors. Consequently, we examined participants in a between-groups design as they performed the Watchkeeper vigilance task. One group of 14 participants performed the task while wearing the ISCAN eye-tracker/pupillometer. The second group of 17 participants performed the Watchkeeper task while cerebral bloodflow was monitored using the TCD system. Preliminary results of this study were presented in a poster at the Society for Computers in Psychology.

For the eye-tracker group of participants, Watchkeeper performance was analyzed as a function of the following independent variables: mean pupil dilation, trend in pupil dilation, mean fixation duration, trend in fixation duration, visual scanning distance (the amount the eyes moved prior to presentation of a threat or nonthreat image), mean saccade distance, blink rate, and trend in blink rate.

| | **Min 1-7** | **Min 8-14** | **Min 15-21** | **Min 22-28** |
|---|---|---|---|---|
| Hit rate (mean percent of targets to which the participant responded) | 90% | 88% | 85% | 82% |
| Response time (mean msec from presentation of target to first response) | 1211 | 1300 | 1343 | 1383 |
| Marksmanship error (mean distance from target to shot, in pixels) | 95 | 91 | 119 | 130 |
| Mean TCD during hits (left hemisphere)<br>Mean TCD during hits (right hemisphere) | 58.13<br>56.83 | 54.78<br>54.93 | 55.32<br>53.77 | 55.18<br>54.54 |
| TCD during misses (left hemisphere)<br>TCD during misses (right hemisphere) | 57.47<br>59.88 | 57.08<br>57.27 | 54.37<br>53.31 | 53.97<br>53.46 |

*NOTES: "hits" and "misses" refer to signal detection outcomes, not marksmanship outcomes. With respect to marksmanship, a distance of 100 translates a shot error of approximately 3 cm on both the horizontal and vertical axis*

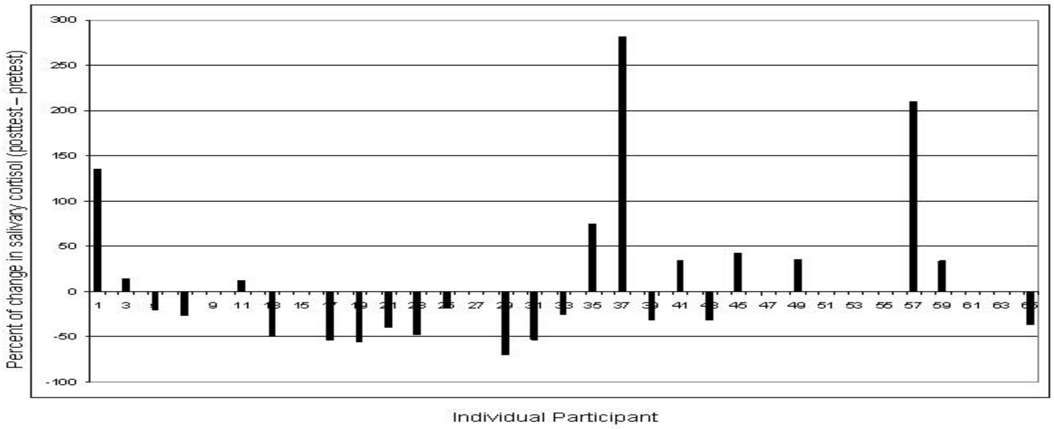
The results indicated a decrement in Watchkeeper performance across the vigil, reflected as a drop in target hit rate (shots when a target is present), an increase in response time, and a decrease in marksmanship accuracy across watchperiods. Trends for hit-rate and response time were linear, whereas the marksmanship measure showed initial improvement before a vigilance decrement in the second half of the task.

For the TCD group, neither left cerebral blood flow nor right cerebral blood flow were found to differ significantly between Watchkeeper hits and misses ($p > .10$ for both $t$-tests). However, speed of bloodflow measures were significantly correlated with variations in Watchkeeper response time and marksmanship accuracy, although the variance accounted for by these prediction was quite small. The speed of blood flow to the left and right hemispheres correlated negatively with variations in response time (i.e., the latency to fire the weapon after presentation of a target stimulus); $r = -.13$ and -.07, respectively. The speed of blood flow to the right hemispheres correlated positively with variations in marksmanship accuracy (i.e., the distance between the location of a shot from the firearm and the center of the target stimulus); $r = .09$ (left hemisphere bloodflow was not significantly correlated with this measure).

Interestingly, a very different pattern of results was obtained from the eye-tracker group. Pupillometric and occulomotor measures did not correlate significantly with marksmanship accuracy or Watchkeeper response time; however, there were significant difference in two of the eye-movement measures in the comparison of signal-detection hits versus misses. That is, they eyes moved significantly more and the pupils were significantly more dilated on trials in which the participants responded to targets than on trials in which the participants ignored targets.

These results show that TCD and eye-movement are associated with different, potentially complementary measures of inattention. This suggests partial support for Hypothesis 2.2.3. It was not possible from these data to examine the combined predictions from TCD and eye-movement indices, because the data were collected on a between-groups basis. This is a significant limitation relative to those we anticipated conducting at GSU; perhaps it will be possible in the future to compare CBFv data from TCD with the output of a table-mounted eye tracker.

d. Relation between salivary cortisol task performance, and TCD. Cortisol levels were assayed from saliva samples, and pre-test / post-test differences were examined to see whether they related to Watchkeeper task performance. However, we found cortisol levels to be highly variable. The figure below, for example, graphs the difference in terms of percent of change [(post-test minus pre-test) divided by pre-test], where 100% would mean cortisol levels doubled from pre- to post-test. Even transforming the scores or discarding outliers left a highly variable sample of scores that were uncorrelated with Watchkeeper latency ($r = 0.06$), decision accuracy ($r = -0.03$), or marksmanship accuracy ($r = 0.13$). A quartile split of those who were most stressed by the Watchkeeper task (i.e., those who showed the largest increases in salivary cortisol between pre- and post-task samples) and those who were least stressed also failed to reveal differences in the performance measures or CBFv (all $p > .10$).




***Study 5, Aim 1 : Test generality of TCD findings with another Army-relevant criterion task***

The Watchkeeper task resisted sustained attention, providing an easy visual discrimination in a task with highly repetitive stimulus events and relatively few responses (i.e., low-probability threat images). To test the generality of these findings, we developed a different shoot/don't-shoot task with increased workload (more difficult stimulus discriminations, response-time pressure, frequent threat images).

Hypothesis 5.1.1: Relationships found in Study 2 between TCD and task performance from will generalize to a new criterion task that requires continuous performance of shoot/don't-shoot judgments—and specifically that task performance will correlate with changes in CBFv, and that TCD measures will predict criterion-task performance.

Hypothesis 5.1.2: Relationships found in Study 2 between TCD and task performance will generalize to a new criterion task that requires new learning of defensive strategies—and specifically that task performance will correlate with changes in CBFv, and that TCD measures will predict individual differences in criterion-task performance.

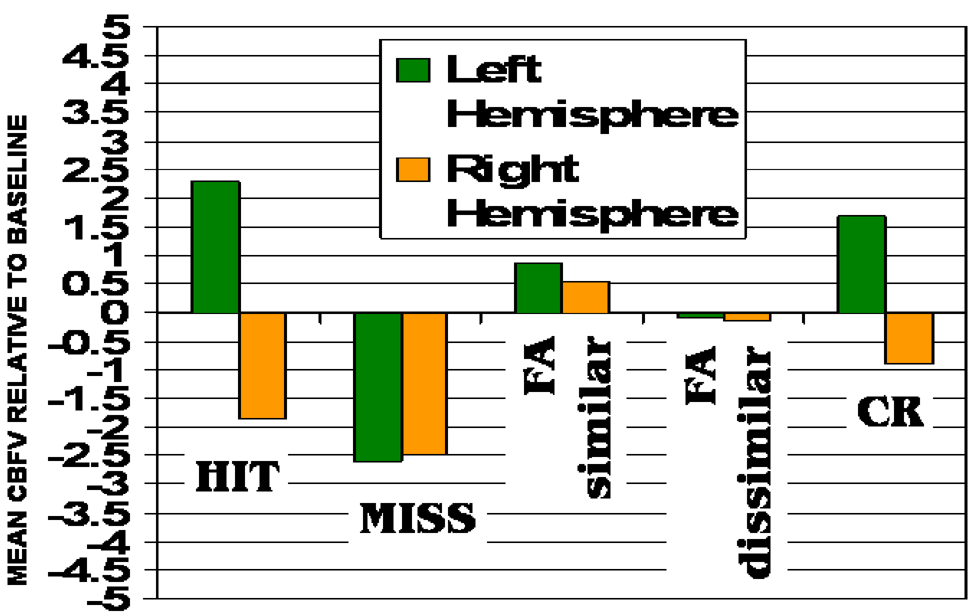
<u>a. Relation of TCD and Peacekeeper performance</u>. Of the 151 participants who contributed data on the Peacekeeper task, 50 also contributed reliable CBFv measures from both cerebral hemispheres. As with the Watchkeeper task, false alarm rates were low (<1%) for the Peacekeeper task. Thus, subsequent signal-detection analyses focused on hit-rate data.

Data were grouped into equal bins, each representing 100 stimulus presentations. Analyses of performance data are displayed in the table below.

| Measure | Period 1 mean (std) | Period 2 mean (std) | Period 3 mean (std) | Period 4 mean (std) | ANOVA |
|---|---|---|---|---|---|
| Hit rate | 0.62 (0.17) | 0.61 (0.20) a | 0.56 (0.22) ab | 0.53 (0.5) b | F(3,450) = 18.0, p < .001 |
| Response latency | 0.976 s (.091) | 0.989 s (.111) a | 1.000 s (.116) a | 1.003 s (.116) | F(3,420) = 7.3, p < .001 |
| Marksmanship error | 15.6 (4.2) a | 16.1 (4.9) ab | 16.8 (5.4) b | 17.0 (5.4) | F(3,420) = 7.8, p < .001 |
| Left CBFv | 2.76 (5.67) a | 0.72 (5.84) ab | 0.01 (6.13) bc | -0.82 (6.60) c | F(3,147) = 37.1, p < .001 |
| Right CBFv | 1.50 (5.17) a | -1.08 (5.94) ab | -1.88 (7.00) bc | -2.90 (7.42) c | F(3,147) = 27.9, p < .001 |

[Lowercase letters indicate consecutive cells that were significantly different in post-hoc comparisons. Marksmanship error is calculated in twips, such that every 10 corresponds to an error of approximately 3 cm in horizontal/vertical distance from the target center. CBFv measures are reported as deviation scores relative to the 2-min resting baseline.]

The Peacekeeper task yields numerous measures for analysis. Signal-detection data (hits, misses, false-alarms on nontargets that were similar to the target stimuli, false-alarms on nontargets that were dissimilar to the targets, and correct rejections) were analyzed to see whether TCD measures differed between the hemispheres. Significant differences were observed between the left-hemisphere CBFv measure and the right-hemisphere CBFv measure on correct decisions (hits and correct rejections), *p* <.05.  No other differences were statistically significant.




Performance index

Averaged across hemispheres, CFBv differed significantly between misses (miss rate = 16%) and all other conditions (each $p < .05$).

A familiar pattern of results was observed in the response-time data from this same task. Here, quartile splits that grouped the fastest participants for comparison with the slowest participants replicated the effects from the Watchkeeper task. Participants who shot (when they were supposed to) most quickly had significantly faster CBFv in the left cerebral hemisphere than the right cerebral hemisphere. The difference between CBFv in the left and right cerebral hemispheres was not significantly different for the group of participants in the bottom quartile for shot latency ($p > .10$); however, the direction of the absolute difference for these participants is comparable to what was reported for the Watchkeeper task.

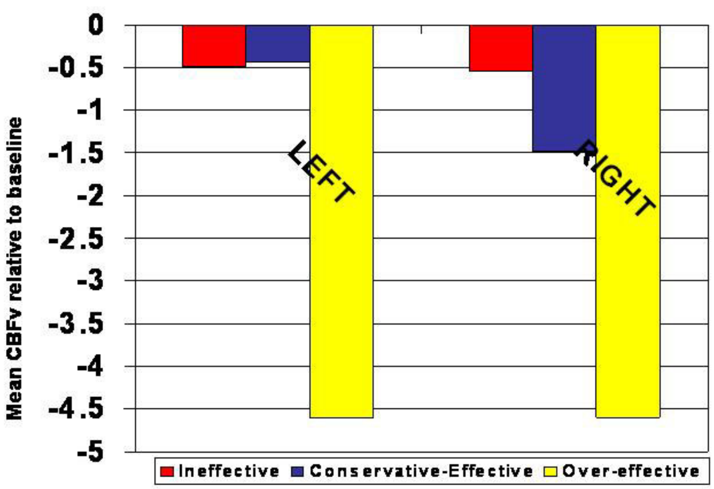
(Note : x-axis labels on 0-line)


b. Relation of TCD and DSO-2 performance. There are three primary measures from the DSO-2 task. One is the number of points per block of trials (or game) as a general measure of learning. A second is the number of "over-reactions" or uses of a defensive strategy that, although effective, is greater (and thus more costly) than demanded by the threat condition.

Mean CBFv for a block of trials was uncorrelated with the number of points earned on those trials ($r = 0.17$, $p > .10$). Similarly, the CBFv of participants who improved their points across blocks did not differ from the CBFv of participants who did not show evidence of learning (-0.5 versus -0.81, respectively; $p > .10$) and the amount of learning (change from the first block of trials to the last block of trials) was not predicted by CBFv measures ($p > .10$). Of course, the sample size was small for these analyses, given that 31 of the 50 participants tested on DSO-2 did not yield reliable bilateral TCD signals. However, differences in the TCD measure were observed between defensive-system deployments that were effective but overly costly and those that were ineffective. Ineffective responses were associated with significantly greater CBFv (i.e., TCD measures closer to baseline) than were effective but over-reactive responses. No difference

in CBFv was observed between ineffective responses and those that were conservatively effective (i.e., at the appropriate defensive level). No difference between the left- and right-hemisphere CBFv was observed. The ANOVA table and a figure showing CBFv as a function of hemisphere and strategy are shown below. The decline in CBFv associated with use of an over-effective strategy is evident in both hemispheres.

| Effect | F | p | df |
|---|---|---|---|
| Hemisphere (Left, Right) | 1.54 | 0.23 | 1,19 |
| Strategy (Ineffective, Conservative, Over-Effective) | 27.07 | <.001 | 2,38 |
| H X S | 1.69 | 0.20 | 2,38 |

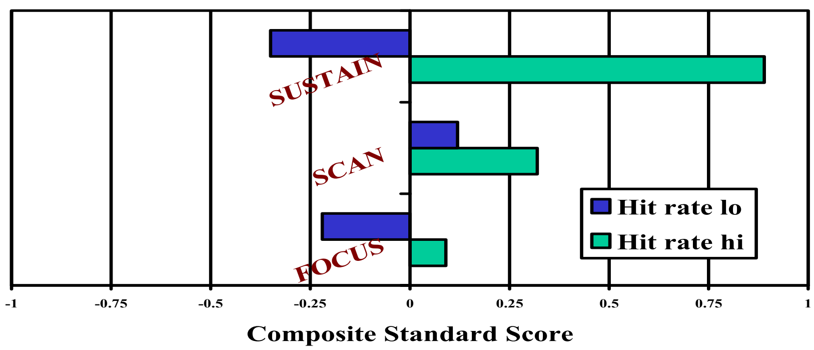



***Study 6, Aim 1 : Examine whether individual-difference factors moderate diagnosticity of TCD on task performance***

Individuals differ in the attention skills that they bring to any test situation. Some participants are better at sustaining attention than are others. Some are better at concentrating or shifting attention than are others. The purpose of this study is to examine the relation between individual differences in attention skills and Watchkeeper task performance and CBFv changes.

Hypothesis 6.1.1: The effects of time-on-task from the Watchkeeper task will not be uniform across participants, but rather some participants (specifically those with strong sustained-attention skills as identified by a separate battery of assessment tasks) will show less pronounced vigilance disruptions.

a. ASAP and Watchkeeper performance. ASAP tasks were used to profile the attention skills of participants, who were also tested on the Watchkeeper task. Composite standard scores on the ASAP tasks were created by combining tasks and measures that had previously been shown to load together on attention factors. Participants were then grouped by quartiles on the Watchkeeper decision accuracy (decisions to shoot on threat trials / total number of threat trials) measures, such that participants with the highest hit rate could be compared to those with the worst hit rate on measures of attention-focusing (i.e., concentration or mental effort), attention scanning or orienting, and attention sustaining or alerting. (Note: false alarms were seldom observed in the Watchkeeper task.) The results of these three comparisons are displayed graphically in the figure below.




Participants who most often shot when a target stimulus was on the screen showed significantly better attention sustaining skills than did the lowest-hit-rate group ($p < .001$). No other differences were statistically significant.

b. ASAP and TCD. TCD data were analyzed while 30 participants performed the ASAP tasks. Two questions were of primary concern for this study: (a) Does TCD vary by watchperiod for the 6-min continuous performance task within the ASAP battery? and (b) Does TCD vary in either hemisphere for the other ASAP tasks. The tables below summarize the descriptive statistics for this study.

**Mean CBFv relative to baseline for each minute of the 6-minute CPT task**

| | Minute 1 | Minute 2 | Minute 3 | Minute 4 | Minute 5 | Minute 6 |
|---|---|---|---|---|---|---|
| Left hemisphere | 1.0 | 0.5 | -0.2 | -0.4 | -0.9 | -1.3 |
| Right hemisphere | 2.0 | -0.1 | -0.5 | -0.5 | -0.9 | -1.0 |

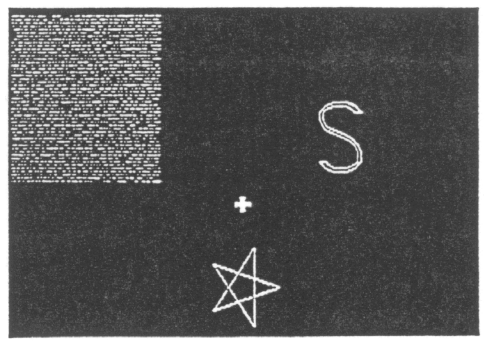
**Mean CBFv relative to baseline for each of six ASAP tasks**

| | Stroop | CPT | Search | Choice RT | Inhib | ANT |
|---|---|---|---|---|---|---|
| Left hemisphere | 3.3 | -0.3 | -0.1 | -1.2 | 3.8 | 0.6 |
| Right Hemisphere | 2.3 | -0.3 | 1.2 | -1.0 | 3.1 | 1.99 |

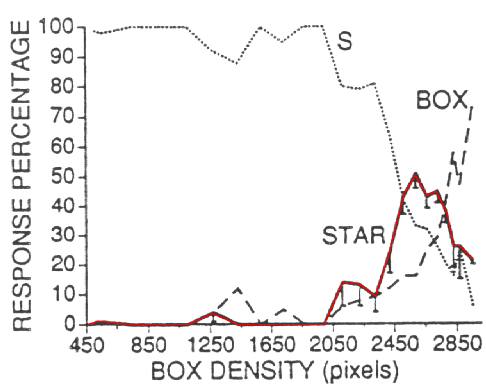
***Addendum (pilot study) : Does TCD predict decision uncertainty?***

As discussed in the General Method, the Watchkeeper, Peacekeeper, and DSO-2 tasks required participants to make dichotomous under conditions that may have engendered uncertainty. However, the tasks gave participants no option for responding to that uncertainty—for requesting more information, for refusing to guess, or even for declaring their lack of confidence about their response to shoot or not, to deploy one defensive system versus another, and so forth.

In collaboration with J. David Smith (U. Buffalo), who developed the uncertainty paradigm, we have examined individual differences in responsiveness to subjective uncertainty using a psychophysical judgment task. Although this task was not part of the funded proposal, we were curious about whether the brain-activity measures from CBFv would relate to task-induced decision uncertainty. Accordingly, a pilot study was administered.




Participants were tested with the task depicted in this figure. Each trial involved the presentation of a box filled with some number of illuminated pixels. If the box was populated with exactly 2,950 illuminated pixels, it was deemed a threat stimulus. In response to this threat, participants were instructed to use the computer keyboard to move the cursor (+) into contact with the box. If the box was filled with any fewer than 2,950 pixels, the participant was to indicate that the stimulus was "safe" by touching the S. Feedback was provided after each trial to indicate whether the participant was correct or incorrect, and to award or deduct points accordingly. Across trials, the number of dots in the box was titrated so that judgments became increasingly difficult as the participant did well (requiring perhaps judgments of whether 2,800 pixels met the "threat" threshold). In this way, the task automatically found the psychophysical threshold where participants could no longer determine whether the box was a threat or not. That is, the task automatically tracked to the region where responses were equally likely to be incorrect and correct, and administered many trials in this region.




Notice a third response option on the screen: the star. Participants could move the cursor into contact with the star on any trial. Touching the star provided additional information so the participant would know whether to touch the box or the S. Although the participants could have used this star-response on any trial, they seldom requested additional help when it was obvious that the box contained fewer than 2,950 pixels. Similarly, most participants avoided the star when the box looked very much like the threat stimulus. Rather, participants tended to use

the star as an "uncertain" or "escape" response on exactly those trials where they were equally likely to be correct or incorrect, that is, in the region where their psychophysical performance showed that the participants were uncertain.

We tested undergraduate volunteers on this psychophysical "uncertainty" task while monitoring CFBv to both hemispheres. Predictably, CBFv was positively correlated with task difficulty ($r$ = 0.20, $p$, < .05). What was surprising about the results of this study is that CBFv was not reliably correlated with participant's use of the star or "uncertain" response ($r = 0.07$, $p > .10$), but it was significantly correlated with empirical uncertainty (the ratio of Safe/Threat responses at each level of task difficulty), $r = 0.31$, $p < .01$. That is, TCD measures provided a reliable indicator that participants <u>were</u> uncertain, even if the participants didn't acknowledge that uncertainty with a star response.

A regression model with CBFv and self-reported uncertainty (use of the star response) predicts empirical uncertainty (the crossover region of the "safe" and "threat" response functions) better than use of the star alone:

$r^2$ (uncertain response) = 0.15, $p < .01$
*delta* $r^2$ (CBFv) = 0.08, $p < .01$

In other words, CBFv accounts for unique variance in predicting a participant's uncertainty, even after removing that portion of the variance associated with the participant's own self-report of uncertainty!

The implication of these findings is intriguing: Perhaps CBFv measures from TCD can indicate that a participant is uncertain about a decision (e.g., to shoot or not) at times that the participant herself/himself may not be monitoring or responding in an adaptive way to that uncertainty. Perhaps TCD can provide a measure of when participants need to ask for help or for more information, a measure that is not dependent on participants willingness to admit their uncertainty or capacity to monitor their decisions metacognitively.

To determine whether this implication is indeed true, additional studies are needed:

1. To replicate and extend the finding from the psychophysical uncertainty paradigm with more than a pilot sample of participants.

2. To demonstrate the effect in an Army-relevant criterion task where risky decision making is required and where monitoring of uncertainty may benefit performance (e.g., Watchkeeper or Peacekeeper, friendly fire scenarios, risky decisions in driving or moving through unsafe environments, etc.).

3. To show whether TCD-triggered cues to participants that they are uncertain would produce better decisions and improved performance (relative to cues that are yoked for frequency but not tied specifically to CBFv states associated with uncertainty).

We would be very pleased if USAMRMC would capitalize on its investment to date by providing additional support to allow these important questions to be answered at GSU and UC.

***Addendum (thesis study) : Does TCD reflect the capacity of visual working memory?***

Two theories have been proposed to explain the capacity limit of visual short-term memory (VSTM). The object-based theory states that visual capacity is limited by the number of objects in a display, whereas the flexible resource theory states that visual capacity is limited by the complexity of the objects. We examined object memory in a change detection task using displays of random polygons that varied in image complexity and the number of objects presented. In conjunction with recognition memory performance, we used transcranial Doppler sonography to measure CBFV as a marker of brain activity. Both performance measures and cerebral CBFV indicated that capacity for random polygons is approximately one object, well below the capacity estimated by object-based theory. Complexity of the objects affected capacity, such that simple objects had higher capacities and lower cerebral blood flow velocity than complex objects, thus lending support to the flexible resource theory.

Forty-two participants (32 females and 10 males) from the Georgia State University research participant pool participated in this study. Age ranged from 18 to 32 with a mean of approximately 20.6 years. Due to the experimental design of researching lateralization effects, only right-handed individuals were recruited to participate in the experiment. All participants were required to have normal or contact corrected–to-normal vision. Participants who wore glasses were excluded, as the frame of eyeglasses interfered with the ability to acquire a signal with the apparatus. Five participants were tested but were not included in data analyses due to a programming problem. One participant was excluded due to failure to follow instruction. Fourteen participants were not included in the analyses because a reliable and stable signal for TCD could not be obtained. Thus, 22 volunteers were included in the final analysis.

Participants were tested on a change-detection memory task. The participant looked at a fixation cross for 200 milliseconds (ms), followed by the target display. The target display contained 1, 2, or 3 stimuli from one object type. The stimuli were presented within an invisible 3 x 3 matrix. The target display was presented for a duration of 1000 ms. The target display was followed by a 2000 ms retention interval of blank black screen. The test display contained one stimulus presented at the center of the screen. In one-half of the trials, the test stimulus was the same as one of the stimuli presented; in the other half of the trials, the test stimulus was changed. The participant was required to press the right mouse button if the stimulus was the same as one in the target display or the left mouse button if the test stimulus was changed (these buttons were labeled accordingly). The test display was presented until the participant responded. Reaction times for responses and the responses themselves were recorded. Correct trials resulted in a series of tones, whereas incorrect responses were followed by a buzzing sound. The intertrial interval was 2000 ms. A blank gray screen was shown between trials.

CBFv was calculated by subtracting each participant's average baseline CBFv from the CBFv

recorded in the one second of stimulus presentation. The baseline average was calculated by averaging the CBFv from two minutes of recording. A two-way 2 (Hemisphere) x 2 (Correct or Incorrect Recognition) ANOVA was conducted comparing CBFV in trials answered correctly to CBFv in trials answered incorrectly for both hemispheres. There was no significant difference in CBFv between trials correctly ($M$ = -2.21, $SE$ = 0.63) or incorrectly answered ($M$ = -1.93, SE = 0.66), $F$ (1, 21) = 3.52, $p$ > .05. There also was no significant difference in CBFv between the right hemisphere and the left hemisphere, nor was the interaction significant. In the following analyses, average CBFv was combined for correct and incorrect trials.

A mixed-design 2 (Order) x 3 (Condition) x 2 (Stimulus type) x 3 (Memory Load) x 2 (Hemisphere) ANOVA with the change in CBFV as the dependent variable was conducted. CBFV was significantly slower for simple stimuli ($M$ = -2.308, $SE$ = .660) than complex stimuli ($M$ = -2.128, $SE$ = .634), $F$ (1, 20) = 4.432, $p$ < .05. Thus, the brain was more activated for complex objects than simple objects.

The Dual-task condition variable included three levels that were: Control ($M$ = -1.825, $SE$ = 0.617), Articulatory Suppression (AS; $M$ = -2.538, $SE$ = 0.901), and Verbal Load (VL; $M$ = -2.290, $SE$ = 0.753). The main effect of condition was not significant. However, the Condition by Order interaction was significant, $F$ (2, 19) = 5.835, $p$ < 0.05. Condition by Hemisphere interaction approached significance, $F$ (2, 19) = 3.481, $p$ = 0.052. The three-way interaction of condition by hemisphere by order was significant, $F$ (3, 18) = 3.201, $p$ < .05. Lastly, the three-way interaction of condition by hemisphere by stimulus type was significant, $F$ (3, 18) = 3.201, $p$ < .05. These effects will be examined further below.

CBFV was similar for both orders of control 1 conditions, but this was expected because participants in both orders would perform this condition first. CBFV dropped from the second block to the third block, regardless of which task (AS or VL) was in the second block. The control 2 condition was faster when it followed AS than when it followed VL.

All other main effects and interactions were not significant ($F$ < 1.00, $p$ > .05). This suggests that brain activation was highest in the control 1 with a memory load of 1 item. For the other conditions, a memory load of 1 item had the lowest amount of activation, although memory load of 2 and 3 had higher amounts of activation than memory load 1, they were similar.
A further analysis was conducted to explore the interactions. As the variable of Dual-task condition was included in each significant interaction, each Dual-task condition was analyzed separately. Separate mixed-design 2 (Order) x 2 (Stimulus type) x 3 (Memory Load) x 2 (Hemisphere) ANOVAs were conducted to analyze the simple effects from the interactions. In the each condition, none of the main effects or interactions were significant.

The analysis of brain activation, as indicated by TCD, provides evidence to support the flexible resource theory above the object-based theory. Cerebral blood flow velocity differed significantly between the two levels of stimulus complexity, with faster blood flow when participants were attempting to remember complex versus simple stimuli. This suggests that mental workload was higher when the to-be-remembered stimuli were more complex. The blood

flow effects, like the performance differences, show that all stimuli are not recognized equally as might be suggested by the object-based theory where the number of slots is fixed and each slot can hold all of any one stimulus.

KEY RESEARCH ACCOMPLISHMENTS

- UC Studies 1 and 2 confirm that reliable and meaningful individual differences in CBFV may be assessed using a short task battery. These phasic response indices may be useful as diagnostic predictors of sustained performance.

- UC Study 1 demonstrated that cognitive vigilance may be stressful and fatiguing as sensory vigilance. Cognitive vigilance is accompanied by declining CBFV in both hemispheres.

- UC Study 1 replicated key findings from the earlier study of sensory vigilance using a cognitive vigilance task placing heavy demands on working memory. Specifically, both phasic bloodflow measures and subjective task engagement predict subsequent cognitive vigilance.

- UC Study 1 confirmed previous research suggesting that standard personality traits are weak predictors of vigilance; cognitive ability tests appear to be more promising.

- UC Study 2 found that prolonged driving on a simulator elicited declines in task engagement and declines in CBFV in both hemispheres similar to those seen in vigilance

- Some subjective correlates of driving performance were demonstrated, but CBFV was not predictive of vehicle control or speed choice.

- The resource-workload model provides a useful theoretical framework for predicting individual differences in vigilance; its applicability to more complex tasks requires further investigation.

- Although the relationship between changes in CBFV and changes in military vigilance-task performance is small, it is statistically significant and appears consistent across tasks (GSU Studies 2 and 5).

- In two different tasks, the relative direction of CBFV changes in the left versus the right cerebral hemispheres was different for participants who made fastest shoot-decisions compared to the participants who made slowest shoot-decisions (GSU Studies 2 and 5).

- Changes in CBFV may be associated with a tendency toward over-reactions to threat conditions (i.e., effective but costly defensive strategies: GSU Study 5).

- Profiles of attention skills differ reliably between those who perform well on shoot/don't-shoot tasks and participants who perform poorly on these tasks (GSU Study 6).

- There is a suggestion from pilot studies that (1) CBFV changes may indicate when a participant is uncertain about a decision, even when the participant doesn't admit (or perhaps recognize) the uncertainty, and (2) effects of performing a VSTM task on CBFV may be accommodated within resource theory.

## REPORTABLE OUTCOMES

### University of Cincinnati

*Articles*

Finomore, V., Matthews, G., Warm, J.S., & Shaw, T. (submitted for publication). Predicting vigilance: A fresh look at an old problem.

Funke, G. J., Matthews, G., Warm, J.S., & Emo, A. (2007). Vehicle automation: A remedy for driver stress? *Ergonomics*, *50,* 1302 – 1323.

Matthews, G. (in preparation). Individual differences in task engagement and attention. In B. Szymura, G. Matthews & A. Gruska (Eds.), *Handbook of individual differences in cognition: Attention, memory and executive control*. New York: Springer.

Matthews, G., & Campbell, S.E. (in press). Sustained performance under overload: Personality and individual differences in stress and coping. *Theoretical Issues in Ergonomics Science.*

Matthews, G., Saxby, D.J., Funke, G.J., Emo, A.K., & Desmond, P.A. (in press). Driving in states of fatigue or stress. In D. Fisher (Ed.), *Handbook of driving simulation in engineering, medicine and psychology*. Boca Raton, FL: Taylor and Francis.

Reinerman, L., Matthews, G., Warm, J.S., & Langheim, L. (2007) Predicting cognitive vigilance performance from cerebral bloodflow velocity and task engagement. *In Proceedings of the Human Factors and Ergonomics Society 51st Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Reinerman, L., Matthews, G., Warm, J.S., Langheim, L., Parsons, K.S., Proctor, C., Siraj, T., Tripp, L.D., & Stutz, R. (2006) Cerebral bloodflow velocity and task engagement as predictors of vigilance performance. *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, pp. 1254-1258. Santa Monica, CA: Human Factors and Ergonomics Society.

Shaw, T., Warm, J.S., Matthews, G., Riley, M., Weiler, E., Dember, W.N., Tripp, L.D., Finomore, V., & Hollander, T. (2006) Effects of sensory modality on vigilance performance and cerebral hemovelocity. *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, pp. 1619-1623. Santa Monica, CA: Human Factors and Ergonomics Society.

Warm, J.S., Matthews, G., & Finomore, V.S. (2008) Workload and stress in sustained attention. In P.A. Hancock and J.L. Szalma (Eds.), *Performance under stress*, pp. 115-141. Aldershot, UK: Ashgate Publishing.

*Presentations*

Reinerman, L.E., Langheim, L., Matthews, G., Warm, J.S., Parsons, K.S., Beam, C.A., & Tripp, L.D. Individual differences in cerebral bloodflow during sustained performance. Stress and bloodflow as predictors of performance. Paper presented at the Ninety-eighth Annual Meeting of the Southern Society for Philosophy and Psychology, Charleston, SC, April 2006.

Matthews, G., Warm, J.S., Proctor, C.A., Parsons, K.S., Reinerman, L.E., Langheim, L., & Tripp, L.D. Cerebral bloodflow and subjective task engagement predict vigilance. Poster presented at 18th Annual Convention of the Association for Psychological Science, New York, May 2006.

Funke, G.J., Matthews, G., Warm, J.S., & Emo, A.K. Effects of vehicle automation, stress and subjective state on performance in a driver simulator. Paper presented at 26th International Congress of Applied Psychology, Athens, Greece, July 2006.

Matthews, G.,Warm, J.S., Langheim, L., Reinerman, L.E., Parsons, K.S., Proctor, C.A., & Tripp, L.D. Cerebral bloodflow and subjective states predict sustained attention. Paper presented at 26th International Congress of Applied Psychology, Athens, Greece, July 2006.

Matthews, G. Individual differences in task engagement and attention. Keynote address, symposium on Individual Differences in Cognition, Krakow, Poland, September 2006.

Langheim, L., Matthews, G., Warm, J.S., & Reinerman, L.E. Effects of task-induced stress of cerebral bloodflow velocity, cortisol, and subjective state. Paper presented at Ninety-ninth Annual meeting of the Southern Society for Philosophy and Psychology, Atlanta, GA, April, 2007.

Reinerman, L.E., Matthews, G., Warm, J.S., Langheim, L., & Even, A. Predicting cognitive vigilance performance: Cerebral bloodflow velocity and task engagement. Poster presented at 19th Annual Convention of the Association for Psychological Science, Washington, DC, May 2007.

Langheim, L., Matthews, G., Warm, J.S., Reinerman, L.E., Shaw, T.H., Finomore, V.S., Funke, M., & Guznov, S. The long pursuit: In search of predictors of individual differences in vigilance. Paper presented at Thirteenth Meeting of the International Society for the Study of Individual Differences, Giessen, Germany, July 2007.

Matthews, G. Human performance, vigilance and cerebral bloodflow. Invited address, Kazakh National University, Almaty, Kazakhstan, August 2007.

Matthews, G. Individual differences in task engagement, cerebral bloodflow and attention. Invited colloquium, University of Oklahoma, February 2008.

Reinerman, L.E., Langheim, L., Matthews, G., & Warm, J.S. Cerebral blood flow velocity and task engagement as predictors of simulated driving performance. Paper presented at One Hundredth Annual meeting of the Southern Society for Philosophy and Psychology, New Orleans, March 2008.

Matthews, G., Warm, J.S., Reinerman, L.E., Langheim, L., Shaw, T.H., Finomore, V.S., Funke, M., & Guznov, S. Cerebral bloodflow velocity and task engagement predict vigilance. Annual Convention of the American Psychological Association (Division 19: Military), Boston, August 2008.

**Georgia State University**

Barrett, N. *The Capacity of Visual Short-Term Memory: A Functional Transcranial Doppler Sonography Study*. Unpublished thesis submitted in partial fulfillment of requirements for the Master of Arts degree, Georgia State University, 2007.

Barrett, N., & Washburn, D. A. (2007, April). Cerebral bloodflow Velocity Predicts Uncertainty in a Metacognitive Task. Paper presented at the annual meeting of the Southern Society for Philosophy and Psychology, Atlanta, GA.

Petridis, A., Barrett, N., & Washburn, D. (2007, March). Gender Differences in Stress Changes during a Decision-Making Task. Poster presented at the Georgia State University Psychology Undergraduate Research Conference, Atlanta, GA.

Cann, A., Barrett, N., & Washburn, D. (2007, March). Effects of Stress States on Shoot/Don't-Shoot Performance. Poster presented at the Georgia State University Psychology Undergraduate Research Conference, Atlanta, GA.

Kerr, J., Barrett, N., & Washburn, D. (2007, March). Stop! Do I Shoot? Individual Differences in Shoot/Don't-Shot Performance. Poster presented at the Georgia State University Psychology Undergraduate Research Conference, Atlanta, GA.

Washburn, D. A., Barrett, N., Matthews, G., & Warm, J. (2007, March). Being Vigilant to Homeland Security. Paper presented in Presidential invited symposium "Psychology in the public interest of homeland security" (David Washburn, organizer & chair) at the annual meeting of the Southeastern Psychological Association, New Orleans, LA.

Barrett, N., & Washburn, D. A. (2006, November). Cognitive and Hemodynamic Predictors of Shoot/Don't-Shoot Decision Making. Poster presented at the annual meeting of the Society for Judgment and Decision Making, Houston, TX.

Barrett, N., & Washburn, D. A. (2006, November). Cerebral bloodflow Velocity Correlates of Factors of Attention. Poster presented at the annual meeting of the Psychonomic Society, Houston, TX.

Barrett, N., Gulledge, J. P., Washburn, D. A. (2006, November). Testing Two Transcranial Technologies. Poster presented at the annual meeting of the Society for Computers in Psychology, Houston, TX.

Washburn, D. A., & Barrett, N. (2006, October). Hemispheric Differences in the Prediction of Inattention Using Transcranial Doppler Sonography. Poster presented at the annual meeting of the Society for Neuroscience, Atlanta, GA.

Washburn, D. A., & Barrett, N. (2006, May). Transcranial Doppler Predicts Response Time and Marksmanship Error in Vigilance Task Performance. Poster presented at the annual meeting of the Association for Psychological Science, New York, NY.

Barrett, N., & Washburn, D. A. (2006, April). Measurement of Mental Activity from Functional Transcranial Doppler Sonography. Paper presented at the annual meeting of the Southern Society for Philosophy and Psychology, Charleston, SC.

Schultz, N.B., & Washburn, D. A. Vigilance Effects on Performance Measures in Shoot/Don't Shoot Task: A Transcranial Doppler Sonography Study (2008, March). Paper presented at the annual meeting of the Southern Society for Philosophy and Psychology, New Orleans, LA.

Note. The majority of these presentations are available upon request.

## CONCLUSIONS

This section summarizes, in brief, the main conclusions that may be drawn from the three-year period of the research grant.

*Psychometrics of cerebral bloodflow measurement.* Studies of CBFV reported prior to this research had focused almost entirely on group data, to the neglect of individual differences. Thus, the diagnostic utility of CBFV changes in the individual operator was unknown. The first step towards investigating individual differences in bloodflow in individuals is to establish that the measures are psychometrically sound; i.e., that they are reliable and valid.

The present research addressed the psychometrics of CBFV in the context of both phasic increases in bloodflow elicited by short tasks, and longer-term declines in bloodflow accompanying sustained performance. In both cases, the task-induced response may be reliably measured within each of the hemispheres. Task-induced responses are largely independent of baseline CBFV, measured without any task imperative. Validity of response was demonstrated by the lateralization of phasic responses, according to task demands.

*Sustained performance and bloodflow change.* A further aim of the research was to examine the generalization of declines in CBFV across a variety of tasks requiring sustained attention. Several of the findings from these studies demonstrate the generality of the effect. A study of feature presence/absence in vigilance (Year 1 report) established that cerebral bloodflow is sensitive to the workload of a vigilance task requiring detection of an absent stimulus element, corresponding to the military task of monitoring for the disappearance from surveillance of an enemy unit. A study of sensory modality showed that CBFV declines during performance of auditory as well as visual tasks (Year 2 report). In addition, cognitive vigilance shows loss of CBFV over time similar to the various sensory tasks employed in this research. Studies also showed decline in CBFV on more complex tasks that go beyond traditional vigilance paradigms, including the Watchkeeper task used in the GSU research, and simulated vehicle driving. Decreased CBFV appears to be the norm for a variety of tasks requiring sustained attention. It should be emphasized that such declines are tied to the workload of the task; our previous studies have shown that simply viewing vigilance stimuli without response over extended periods of time is fatiguing, but does not influence bloodflow.

The data support the position that declining cerebral bloodflow is a concomitant of loss of functional resources in a variety of attentional task paradigms. Further work is needed to address causal relationships between bloodflow, cognitive resource availability and the neurological processes that support attention. It is unclear whether interventions that raise

bloodflow would also directly improve attention. This issue is important for transitioning the research to applied settings, as discussed below.

*Utility of subjective state measures as diagnostic indices*. Demanding vigilance tasks consistently elicit large-magnitude state changes characterized by increased distress and decreased task engagement. A similar response pattern was seen in the two studies of simulated driving. Although CBFV may be more directly linked to task workload, subjective measures may also be useful in evaluating the impact of the task environment on the operator. Subjective state changes may also correspond to changes in coping strategy; for example, loss of task engagement may be accompanied by decreasing task-focus and increasing avoidance coping. Two of the studies also showed that task engagement correlates to a modest degree with higher phasic CBFV, suggesting that both measures may index a common resource mobilization process.

*Prediction of individual differences in sustained performance.* Current research has made only limited progress in identifying psychophysiological indices that predict future sustained performance. The present research demonstrated that individual differences in CBFV may be useful for this purpose. Two studies at UC showed that phasic increases in CBFV predicted subsequent sensory and cognitive vigilance; both hemispheres were implicated. Studies at GSU demonstrated predictive validity for CBFV using measures taken from within the period of work itself. The Watchkeeper task simulates the vigilance and marksmanship of the sentry. Changes in left-hemisphere CBFV predicted performance; concurrent correlations between CBFV and performance were also found.

The Watchkeeper task also showed a consistent tendency for lateralization of CBFV to relate to speed and accuracy of marksmanship. Superior performance was seen in individuals with higher CBFV relative to baseline in the left hemisphere than in the right hemisphere. A similar finding was obtained using the Peacekeeper task, which simulates the speeded shoot/don't-shoot decisions required in peacekeeping operations. These lateralization effects were not found in the UC vigilance tasks, implying that they may be related to the unique decision-making and/or rifle-shooting elements of the GSU simulations of military operations. Studies at GSU also suggested that CBFV may be diagnostic of high-level cognitions, in terms of choosing a defensive strategy against threat (defensive systems operation), and of response to uncertainty. TCD may provide a better index than subjective report of when operators need further information to resolve uncertainty.

The research also compared CBFV with other potentially diagnostic indices. Studies at UC confirmed earlier findings that subjective task engagement is a reliable predictor of high-workload vigilance tasks. Participants who reported higher engagement during the short task battery showed higher perceptual sensitivity during subsequent sensory and cognitive vigilance tasks. Task engagement may index both the capacity of the reservoir of attentional resources, and the effectiveness of coping in states of fatigue and stress. One out of the two studies of simulated driving (reported in Year 1) also showed that task engagement relates to superior control of vehicle trajectory. A study in GSU (reported in Year 2) found that TCD predicted different measures of inattention on the Watchkeeper task to oculomotor and pupillometric indices. Although salivary cortisol is potentially useful as an index of activation of the hypothalamic–pituitary–adrenocortical (HPA) axis, it was not found to be useful as a performance predictor

here. It is possible that the higher levels of stress of operational environments are required to demonstrate diagnosticity.

Results from both laboratories support a multivariate approach to prediction of performance. Diagnosis of the operator's fitness to perform may be maximized by supplementing TCD with subjective and oculomotor indices. Regression models confirm that use of multiple predictors increase the variance in performance criteria explained. Indeed, these multivariate models provide a higher level of predictive validity than typically reported in the vigilance literature.

*Utility of personality and ability measures*. In general, conventional trait measures were only weakly predictive of performance, again reinforcing the need for innovative research on individual differences in sustained attention. However, traits may be used as predictors of subjective stress and fatigue, and the specialized driver stress vulnerability traits showed some promise as predictors of driver stress and performance, depending on task configuration. Cognitive ability tests may be more useful, at least in predicting cognitive vigilance tasks. The sustaining attention ability factor of the GSU attentional skills test battery may also be predictive of performance, as evidenced by data from the Watchkeeper task.

*Transitioning the research.* The present findings confirm and extend existing research in demonstrating that TCD provides an effective means for monitoring vulnerability to performance deficit across a range of tasks requiring sustained attention. In the military context, these include sentry duty, monitoring tactical displays, monitoring unmanned aerial and surface vehicles, vehicle operation, and sustained decision-making. The prevalence of the CBFV decline indicates that TCD may be valuable for assessment of military task environments for the likelihood of cognitive decline. The individual-level data suggest that declining CBFV signals a vulnerability to attentional impairment which may be realized in a subset of individuals. As noted in our original proposal, technology-driven changes to the nature of soldering are liable to increase the need for diagnostic monitoring of this kind. For example, the Year 1 vehicle driving study explored the interaction of stress factors with vehicle automation.

The results of this research also point the way forward to development of predictive task batteries that will provide a quick and valid assessment of the readiness of the soldier on the battlefield for continued engagement in missions requiring sustained attention and alertness, possibly in stressful and fatiguing environments. The phasic increases in CBFV seen in response to short tasks can be reliably assessed in a short time period (although some advances in recording technology may be needed for assessment under operational conditions, to ensure valid signal acquisition). Failure to exhibit an increase in CBFV may be an index of lack of capacity to mobilize attentional resources in response to the challenges of task performance. The research also provides several means of enhancing predictive validity through combining assessment of TCD with other indices that are independently predictive, including systematic subjective state evaluation, attentional profiles, and oculomotor and pupillometric indices. Potentially, a fairly accurate field kit of tests may be devised.

Finally, the research provides some intriguing suggestions for the utility of TCD assessment beyond the problem of vigilance to which it has been initially addressed. The studies at GSU show that CBFV may relate to higher-level tactical decision making, and to management of uncertainty. Further basic research is necessary to understand these relationships further, but

features of CBFV such as its lateralization during sustained performance may prove to have additional diagnostic utility.

*Future research priorities.* The current research may provide a platform for both applied and transitional research. First, given that declining TCD is an index of potential cognitive deterioration, it is important to explore techniques for arresting or reversing the decline. Future research may address the efficacy of the range of techniques explored in relation to fatigue interventions. These include work scheduling and rest breaks, pharmacological interventions, motivational factors, and the intrinsic interest of the task. Conversely, stress factors that may accelerate decline in CBFV, such as sleep deprivation, should also be investigated. Second, as previously indicated, the research has made progress in identifying multiple predictors, including TCD, which might be used for diagnostic prediction. Further research may be directed towards assembling a prototype kit of diagnostic measures, evaluating its utility in predicting sustained performance in the field, and optimizing the choice of predictive measures. It is important also to investigate the range of tasks that TCD may predict. In particular, its utility for predicting performance of multi-component tasks that are more complex than traditional monitoring tasks remains to be systematically evaluated. Third, further research is needed to address the utility of TCD in predicting decision-making and response to uncertainty and risk, as indicated by the GSU studies.

**REFERENCES**


Davies, D.R., & Parasuraman, R. (1982). *The psychology of vigilance*. London: Academic Press.

Dickerson, S.S., & Kemeny, M.E. (2004). Acute stressors and cortisol responses: A theoretical integration and synthesis of laboratory research. *Psychological Bulletin, 130,* 355-391.

Fan, J., McCandliss, B. D., Flombaum, J. I., Thomas, K. M., & Posner, M. I. (2003). Cognitive and brain consequences of conflict. *Neuroimage*, 18,42–57.

Fan, J.M., McCandliss, B. D., Sommer, T.; Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience 14*, 340-34

Funke, G. J., Matthews, G., Warm, J.S., & Emo, A. (2007). Vehicle automation: A remedy for driver stress? *Ergonomics*, *50,* 1302 – 1323.

Hart, S.G., & Staveland, L.E. (1988). Development of NASA-TLX : Results of empirical and theoretical research. In P.A. Hancock and N. Meshkati (Eds.), *Human mental workload* (pp. 139- 183). North-Holland: Elsevier Science Publishers.

Hancock, P.A., & Hart, S.G. (2002). Defeating terrorism;What can human factors/ergonomics offer. *Ergonomics and Design, 10,* 6-10.

Hitchcock, E.M., & Matthews, G. Multidimensional assessment of fatigue: A review and recommendations. International Conference on Fatigue Management in Transportation Operations, Seattle, WA, September 2005.

Hitchcock, E.M., Warm, J.S., Matthews, G., Dember, W.N., Shear, P.K., Tripp.L.D., Mayleben, D.W., & Parasuraman, R. (2003). Automation cueing modulates cerebral bloodflow and vigilance in a simulated air traffic control task. *Theoretical Issues in Ergonomic Science, 4,* 89-112.

Hollander, T.D., Helton, W.S., Tripp, L., Parson, K., Warm, J.S., Matthews, G., Dember, W.N., & Parasuraman, R. (2003) Cerebral vascularity and performance on an abbreviated vigilance task. In *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting,* pp. 1663-1667. Santa Monica, CA: Human Factors and Ergonomics Society.

Matthews, G. (August, 2007). Human performance, vigilance and cerebral bloodflow. Invited address, Kazakh National University, Almaty, Kazakhstan.

Matthews, G., Davies, D. R., & Holley, P. J. (1993). Cognitive predictors of vigilance. *Human Factors, 35,* 3–24

Matthews, G., & Davies, D. R., Westerman, S.J., & Stammers, R. B. (2000). *Human performance: Cognition, stress, and individual differences.* Hove, England: Psychology Press/Taylor & Francis.

Matthews, G., & Desmond, P.A. (2002). Task-induced fatigue states in simulated driving performance. *Quarterly Journal of Experimental Psychology, 55,* 659-686.

.

Matthews, G., Desmond, P.A., Joyner, L.A., & Carcary, B. (1997). A comprehensive questionnaire measure of driver stress and affect. In . E. Carbonell-Vaya & J.A. Rothengatter (Eds.), *Traffic and transport psychology: Theory and application* (pp. 317-326). Amsterdam: Pergamon Press.

Matthews, G., Warm, J.S., Dember, W.N., Mizoguchi, H., & Smith, A.P. (2001) The common cold impairs visual attention, psychomotor performance and task engagement. In *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting,* pp. 1377-1381. Santa Monica, CA: Human Factors and Ergonomics Society.

Matthews, G., Joyner, L., Gilliland, K., Campbell, S.E., & Huggins, J., & Falconer, S. (1999) Validation of a comprehensive stress state questionnaire: Towards a state 'Big Three'? In I. Mervielde, I.J. Deary, F. De Fruyt, & F. Ostendorf (Eds.), *Personality psychology in Europe* (Vol. 7), pp. 335-350. Tilburg: Tilburg University Press.

Matthews, G., Campbell, S.E., Falconer, S., Joyner, L., Huggins, J., Gilliland, K., Grier, R., & Warm, J.S. (2002). Fundamental dimensions of subjective state in performance settings: Task engagement, distress and worry. *Emotion, 2,* 315-340.

Matthews, G., & Davies, D.R. (1998) Arousal and vigilance: The role of task factors. In R.B. Hoffman, M.F. Sherrick, & J.S. Warm (Eds.), *Viewing psychology as a whole: The integrative science of William N. Dember,* pp. 113-144. Washington, DC: American Psychological Association.

Matthews, G., Warm, J.S., & Washburn, D. (2004). *Diagnostic Methods for Predicting Performance Impairment Associated with Combat Stress*. Annual report for U.S. Army Medical Research and Materiel Command (award # W23RYX-3106-N605).

Matthews, G., & Campbell, S.E. (1998) Task-induced stress and individual differences in coping. In *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*, pp. 821-825. Santa Monica, CA: Human Factors and Ergonomics Society.

Matthews, G., Warm, J.S., & Washburn, D. (2004). *Diagnostic Methods for Predicting Performance Impairment Associated with Combat Stress*. Annual report for U.S. Army Medical Research and Materiel Command (award # W23RYX-3106-N605).

Matthews, G., Warm, J.S., & Washburn, D. (2005). *Diagnostic Methods for Predicting Performance Impairment Associated with Combat Stress*. Annual report for U.S. Army Medical Research and Materiel Command (award # W23RYX-3106-N605).

Philip, P., Taillard, J., Klein, E., Sagspe, P., Charles, A., Davies, W.L., Guilleminault, C & Bioulac, B. (2003). Effect of fatigue on performance measured by a driving simulator in automobile drive. *Journal of Psychosomatic Research 55,* 197-200.

Rose, C.L., Murphy, L.B., Byard, L., & Nikzad, K. (2002). The role of the big five personality factors in vigilance performance and workload. *European Journal of Personality, 16,* 185-200.

Reinerman, L., Matthews, G., Warm, J.S., Langheim, L., Parsons, K.S., Proctor, C., Siraj, T., Tripp, L.D., & Stutz, R. (2006) Cerebral blood flow velocity and task engagement as predictors of vigilance performance. *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, pp. 1254-1258. Santa Monica, CA: Human Factors and Ergonomics Society.

Rueda, M.R., Fan, J., McCandliss, B.D., Halparin, J.D., Gruber, D.B., Lercari, L.P., & Posner,M.I. (2004). Development of Attentional Networks in Children. *Neuropsychologia, 42,* 1029-1040.

See, J.E., Howe, S.R., Warm, J.S., & Dember, W.N. (1995). Meta-analysis of the sensitivity decrement in vigilance. *Psychological Bulletin, 117*, 230-249.

Stroobant, N., & Vingerhoets, G. (2000). Transcranial Doppler Ultrasonography Monitoring of Cerebral Hemodynamics During Performance of Cognitive Tasks: A Review. *Neuropsychology Review*, *10*, 213-231.

Szalma, J.L, Warm, J.S., Matthews, W.N., Weiler, E. M., Meier, A., Eggemeier, F. T.. (2004), Effects of sensory modality and task duration on performance, workload, and stress in sustained attention. *Human Factors*, *46*, 219-233.

Thiffault, P., & Bergeron, J. (2003). Fatigue and individual differences in monotonous simulated driving. *Personality and Individual Differences,34,*159-176.

Tripp, L.D., & Warm, J.S. (2007). Transcranial Doppler sonography. In R. Parasuraman & A.M. Rizzo (Eds.), *Neuroergonomics: The brain at work* (pp. 82-94). Cambridge, MA: MIT Press.

Washburn, D.A., & Putney, R.T. (1999). *Assessment Software for Attention Profiles: Final Report.* Unpublished technical report submitted to the U.S. Air Force Office for Scientific Research.

Warm, J.S., & Dember, W.N. (1998). Tests of a vigilance taxonomy. In R.S. Hoffman, M.F. Sherick, & J.S. Warm (Eds.), *Viewing psychology as a whole: The integrative science of William N. Dember* (pp 87-112). Washington, DC: American Psychological Association..

Warm, J.S., Matthews, G., & Finomore, V.S. (in press) Workload and stress in sustained attention. In P.A. Hancock and J.L. Szalma (Eds.), *Performance under stress.* Aldershot, UK: Ashgate Publishing.

Warm, J.S., & Parasuraman, R. (2007). Cerebral hemodynamics and vigilance. In R. Parasuraman & M. Rizzo (Eds.), *Neuroergonomics:The brain at work,* (pp. 156-158). Cambridge, MA: MIT Press.

Wickens, C.D., & Hollands, J.G. (1999). *Engineering psychology and human Performance* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.

.